THE UNIVERSITY OF ALBERTA

THE EFFECT OF FINES ON THE PIPELINE FLOW OF SAND-WATER MIXTURES

by

CHARLES D. D. HOWARD, B.Sc.

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

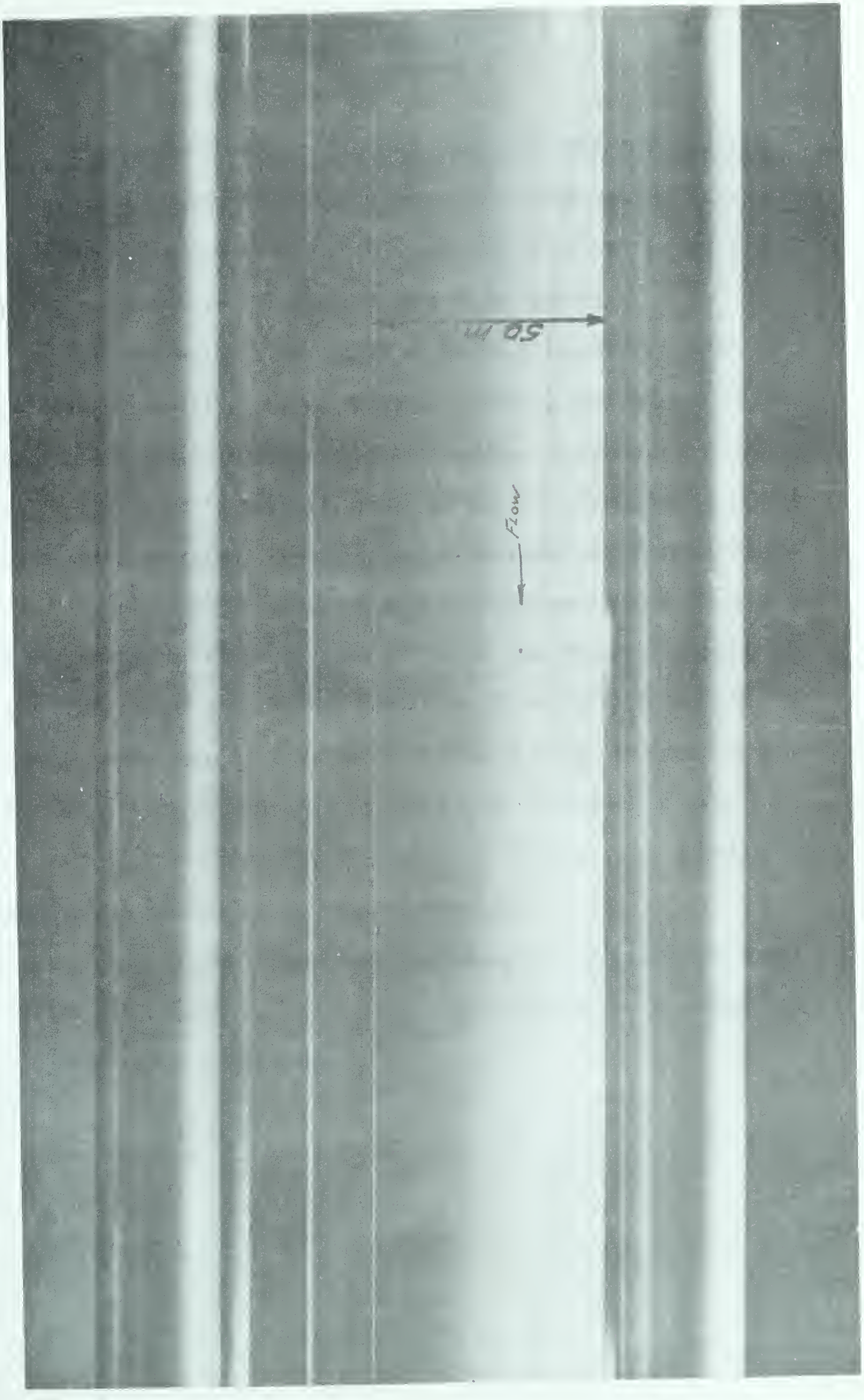
OF MASTER OF SCIENCE

DEPARTMENT OF CIVIL ENGINEERING

EDMONTON, ALBERTA

October 11, 1962

PLATE I



FRONTISPIECE

SAND DUNE MOVEMENT IN THE TRANSPARENT PLASTIC PIPE.

ABSTRACT

A series of tests in a 2-inch pipeline have been carried out on water, sand-water slurries and fines-sand-water slurries to investigate the effect of the addition of fines on the transportation characteristics of a sand-water slurry.

The sand-water slurry data on hydraulic gradient agree with published results of other workers. Testing carried out at low velocities indicate that the published correlations for critical velocity should be slightly modified for a 2-inch pipe carrying sand-water slurries. An alternative correlation is put forth.

The fines-water slurries data are analysed using the rheological characteristics of the mixture at low Reynolds numbers and the theoretical approach of Newitt et al in fully turbulent flow.

An extension to the theory of Newitt et al is made to account for the effect of introducing fines into a sand-water slurry.

It is shown that the introduction of fines into a sand-water slurry can reduce the critical velocity.

A description of the test apparatus is included with a detailed discussion on the instrumentation which was developed during the research program.

TABLE OF CONTENTS

LIST OF PLATES . . . . (i)

LIST OF FIGURES . . . . (ii)

LIST OF SYMBOLS . . . . (iii)

ACKNOWLEDGMENTS . . . . (v)

CHAPTER I - INTRODUCTION. 1

CHAPTER II - EXPERIMENTAL PROGRAM: 6

Flow Sheet 6
Materials Used for Slurry Tests 8
Experimentsl Apparatus 12
Instrumentation 17
Experimental Procedure 27
Accuracy of Results 29

CHAPTER III - THEORY: 30

Homogeneous Mixtures 31
Heterogeneous Mixtures 31
Fines in Sand-Water Mixtures 33

CHAPTER IV - DISCUSSION OF RESULTS:. 35

Clear Water Tests 35
Sand-Water Tests 35
Fines-Water Tests 43
Sand-Fines-Water Tests 47

CHAPTER V - CONCLUSIONS AND RECOMMENDATIONS: 50

Conclusions 50
Recommendations 51

LIST OF REFERENCES 52

* * * * *

LIST OF PLATES

PLATE I	-	FRONTISPIECE. SAND DUNE MOVEMENT IN THE TRANSPARENT PLASTIC PIPE.	
PLATE II	-	TRANSPARENT PLASTIC OBSERVATION PIPE.	Page 16
PLATE III	-	2" MANOMETER TAPS IN 20.5-FOOT TEST SECTIONS.	Page 16
PLATE IV	-	2" MANOMETER TAP, IN 12-FOOT TEST SECTION.	Page 20
PLATE V	-	VIEW OF 2" TEST PIPE.	Page 20
PLATE VI	-	VIEW OF MANOMETER SYSTEM.	Page 22
PLATE VII	-	MANOMETER MANIFOLD.	Page 24
PLATE VIII	-	BACK-PRESSURE CELL.	Page 24
PLATE IX	-	RESERVOIR CELL.	Page 26
PLATE X	-	SEDIMENT TRAPS.	Page 26
PLATE XI	-	TEST RUN MANOMETER READINGS.	Page 28

LIST OF FIGURES

FIGURE 1	-	FLOW DIAGRAM - SAND SLURRY EQUIPMENT	Page 7
FIGURE 2	-	GRAIN-SIZE CURVE FOR SAND GRAINS	Page 9
FIGURE 3	-	GRAIN-SIZE CURVE FOR TOTAL SOLIDS	Page 9
FIGURE 4	-	PHOTOMICROGRAPH OF SAND GRAINS	Page 11
FIGURE 5	-	CHARACTERISTIC CURVES FOR PUMPS	Page 13
FIGURE 6	-	2-inch TEST PIPE SHOWING LOCATION OF MANOMETER TAPS AND PLAN VIEW OF TEST PIPE	Page 15
FIGURE 7	-	SCHEMATIC DIAGRAM OF MANOMETER SYSTEM	Page 18
FIGURE 8	-	PRESSURE DROP vs. VELOCITY FOR CLEAR WATER IN 2-inch PIPE	Page 36
FIGURE 9	-	COMPARISON OF DATA TO PUBLISHED CORRELATIONS	Page 38
FIGURE 10	-	THE EFFECT OF SETTLING VELOCITY ON DURAND'S EQUATION	Page 40
FIGURE 11	-	DURAND'S CORRELATION FOR MINIMUM NON-CLOGGING VELOCITY	Page 41
FIGURE 12	-	COMPARISON OF DURAND'S CRITICAL VELOCITY TO U. of A. DATA FOR SAND-WATER MIXTURES IN 2-inch PIPE	Page 42
FIGURE 13	-	PRESSURE DROP vs. VELOCITY FOR SAND-WATER MIXTURES IN 2-inch PIPE	Page 44
FIGURE 14	-	PRESSURE DROP vs. VELOCITY FOR FINES-WATER MIXTURES IN 2-inch PIPE	Page 46
FIGURE 15	-	EFFECT OF 9% FINES ON A 10% SAND SLURRY	Page 48
FIGURE 16	-	EFFECT OF 10% FINES ON A 10% SAND SLURRY	Page 49

LIST OF SYMBOLS

C = Total concentration of solids in the conveyed mixture expressed as the ratio of total volume of solid material in a sample to the total volume of the sample.

C_s = Concentration of sand in the conveyed mixture.

C_f = Concentration of fines in the conveyed mixture.

C_f^1 = Concentration of fines in the fines-water portion of a three-component mixture.

D = Pipe diameter in feet.

d = Particle grain-size in millimeters.

f_w = Darcy-Weisbach friction factor for clear water.

f_m = Darcy-Weisbach friction factor for mixture.

g = Acceleration due to gravity in feet per second per second.

i_m = Hydraulic gradient for mixture in feet of water per foot of pipe.

i_w = Hydraulic gradient for clear water in feet of water per foot of pipe.

i_{fw} = Hydraulic gradient of the fines-water mixture in feet of water per foot of pipe.

i_{sw} = Hydraulic gradient of the sand-water mixture in feet of water per foot of pipe.

i_{fsw} = Hydraulic gradient of the fines-sand-water mixture in feet of water per foot of pipe.

j = Hydraulic gradient in feet of mixture per foot of pipe. May be used with subscripts as above.

K, K_1, K_2 = Constants for sand-water mixtures.

ΔP = Pressure drop in pounds per square foot per lineal foot of pipe.

ρ_w = Mass density of water in slugs per cubic foot.

ρ_m = Mass density of mixture in slugs per cubic foot.

ρ_f = Mass density of fines particle in slugs per cubic foot.

ρ_s = Mass density of sand particle in slugs per cubic foot.

$\mathcal{V}$ = Volume in cubic feet.

s = Specific gravity of mixture.

s_c = Specific gravity of clay particle.

s_s = Specific gravity of sand particle.

V = Mean velocity of flow based on the cross-sectional area of the pipe in feet per second.

W = The terminal settling velocity of sand particles in still water in feet per second.

W_f = The terminal settling velocity of sand particles in homogeneous fines-water mixtures in feet per second.

V_c = Critical velocity which corresponds to the minimum non-clogging velocity in feet per second.

ACKNOWLEDGMENTS

The test data used herein were collected during part of a research program sponsored by Cities Service Athabasca, Inc. Grateful acknowledgment is made for the financial assistance, technical advice and encouragement furnished by the Company and its employees.

Assistant Professor J. B. Nuttall offered considerable help in developing the theory.

L. Ekman constructed much of the test equipment and provided valuable practical advice.

Particular thanks are due to Assistant Professor R. W. Ansley, who combined the duties of faculty advisor with his strong personal interest in the topic. His contagious enthusiasm was a constant source of inspiration.

CHAPTER I

INTRODUCTION

This thesis deals with one phase of a commercially sponsored research program currently being carried out in conjunction with the Civil Engineering Department of the University of Alberta under the direction of Professor R. W. Ansley.

In general, the program is designed to investigate both the fundamental characteristics and possible commercial applications of hydraulic transport of fluidized solids. A testing unit was built in the Hydraulics Laboratory at the University of Alberta, using funds supplied by the sponsor. The author operated the apparatus and collected the experimental data in conjunction with other aspects of the research program. The work was carried out during two academic years as a research assistant and during the intersessional period of four months as an employee of the sponsor.

Many commercial operations such as mining, ore concentrating, dredging and power plant coal handling have employed hydraulic transport of solids. These developments have given significant impetus to fundamental research in the areas of hydraulic transport of fluidized solids. There is a great deal of literature available dealing with the pumping of sand, gravel, coal and other large particles of material heavier than water. To date, the bulk of this work has been experimental and the published results are empirical equations based on the data obtained from the particular material that was investigated.

Similarly, with the development of drilling mud techniques, considerable literature is available dealing with the pumping of fairly thick, so-called "homogeneous" fluids consisting of suspended solids of the clay size range (fines). The publications dealing with these slurries are somewhat more theoreticl than those for the coarse solids-water mixture, in that a homogeneous fines-water slurry generally exhibits non-Newtonian behaviour as the concentration of fines increases.

In many instances the commercial operator finds two streams of solids to deal with: namely, a coarse solid such as sand or tails and a fine solid such as clay or slimes. In the case of many commercial ore concentrators, these streams are usually present as a low-concentration solids-water slurry. Although these streams are blended in some instances and then disposed of, they are usually conveyed to their disposal areas separately and quite often entirely different methods of conveyance are employed. For example, the tailings are quite often moved to the disposal area in a low-sloped flume, whereas the fines are carried as a dilute slurry in a pipeline. When the two streams were blended and then disposed of via a flume, some operators noticed that the solids carrying capacity at a given slope was increased substantially due to the presence of the fines. In other words, at the same slope the flume carried a greater amount of tailings without deposition of the solids on the bottom of the flume. Dredging operators frequently use this phenomenon by using fines-water slurries instead of clear water to unplug discharge lines filled with sand or gravel.

The investigation carried out by the author attempts to put some qualitative and quantitative interpretation on the effect of introducing fines into a sand-water slurry being transported in pipes under pressure.

Since there are extensive data published on sand-water slurries and fines-water slurries, it seemed reasonable first to select the materials to be conveyed and investigate them separately. This would mean that the sand to be conveyed in the tests would be pumped in a sand-water slurry and then compared against published data. The fines-water slurries were somewhat more complex, because in addition to the pumping tests a rheological investigation of such slurries was necessary to determine their non-Newtonian characteristics. Finally, the two materials were mixed with water in different concentrations of each and pumped for test comparisons.

The first sand-water slurry test runs were conducted on the apparatus as it was originally designed in 1960. After over a hundred test runs, it became apparent that the instrumentation left something to be desired. One of the major items of the investigation carried out by the author was to develop a reliable, simple method of measuring pressure drops which could give results that were reproducible. Several months' experimental and development work were necessary to arrive at the pressure drop instrumentation described herein.

A great deal of the emphasis in the fluidized solids research program has been on flume transport of various slurries. Since the pipeline and flume were connected in series, many data taken on the pipeline

were for runs specifically designed for flume testing. As the flume testing was very sensitive to concentration of solids, the test data were not collected over as wide a range as could have been selected for pipeline research only.

Basically, two specific items were investigated in this program. The pressure drop or energy gradient for various concentrations of the different slurries was measured in the pipeline of the test apparatus. This investigation was standard in that it was hoped that it could provide empirical equations that could be used in the design of a proposed commercial installation. Since high maintenance costs are attendant with the hydraulic conveyance of abrasive solids, there is considerable emphasis on operating the pipeline at as low a velocity as possible. The lowest permissible velocity is that at which the solids being carried in the pipeline do not deposit on the bottom and thus restrict the flow through the pipe. A literature review was undertaken to establish whether the published data could provide any information on either of the two problems.

Considerable literature is available on slurries of sand and water but none was found for sand-fines-water slurries on the subject of energy gradient. Some of the literature on fines-water slurries indicates that if the slurry were homogeneous, a different type of turbulence would be present in the pipeline than that associated with water. This literature does, however, note that such homogeneous slurries are usually non-Newtonian fluids. The energy gradients associated with the pumping of fines slurries over a wide range of concentrations were available in the literature.

In the case of sand slurries, there has been experimental work carried out to establish the lowest velocity at which the material can be pumped before it deposits on the bottom of the pipe. This velocity is referred to as the "non-clogging" velocity or, simply, as the "critical" velocity. Since the fines slurries are considered homogeneous and for the most part do not settle unless the concentrations are extremely high, there are virtually no published data describing the minimum velocity at which the material settles. The author knows of no literature available which describes critical velocity data for sand-fines-water mixtures.

A semi-theoretical explanation of a sand-water slurry has been given by Newitt. This explanation has been extended herein to include the effect of fines. If the hypothesis were correct, it indicates that the addition of fines to the sand-water slurry would decrease the energy gradient at low velocities in the pipeline, and increase it at high velocities. It further predicts that the critical velocity would be lower due to the presence of fines.

The original data are included in Ref. 3 and are also available through the Civil Engineering Department at the University of Alberta.

CHAPTER II

EXPERIMENTAL PROGRAM

Flow Sheet:

The basic flow diagram can be seen in FIGURE 1. Essentially, it is a system designed to mix up a slurry of solids and water, pump it through a centrifugal pump to different-sized pipelines and return it for recirculation. The return line can be either a pipeline or a flume. The original flow sheet has been discussed in some detail by Ansley and Hebbert (Ref. 1). Although the flow sheet has changed somewhat since the initiation of the program in 1960, the modifications have been for ease of operation or to provide facilities to gain a wider range of experimental results. The basic concept of a recirculating stream of a slurry of constant proportions of water and solids has not been changed. Since the circulating stream was either a two- or a three-component mixture, one of the most acute problems was that of determining the actual physical makeup of the mixture.

It was felt that this could best be accomplished by catching a large sample of the mixture in a weigh tank over a long period of time to measure both the weight discharge rate and the volume discharge rate. Representative grab samples were analysed in the laboratory to determine the concentration of the three components of the mixture.

When the total stream was diverted into the weigh tank, the amount of slurry in the circulating system was reduced by the amount which was placed into the weigh tank, thus reducing the level in the sump tank. To avoid this decrease in the sump tank level and a possible decrease in

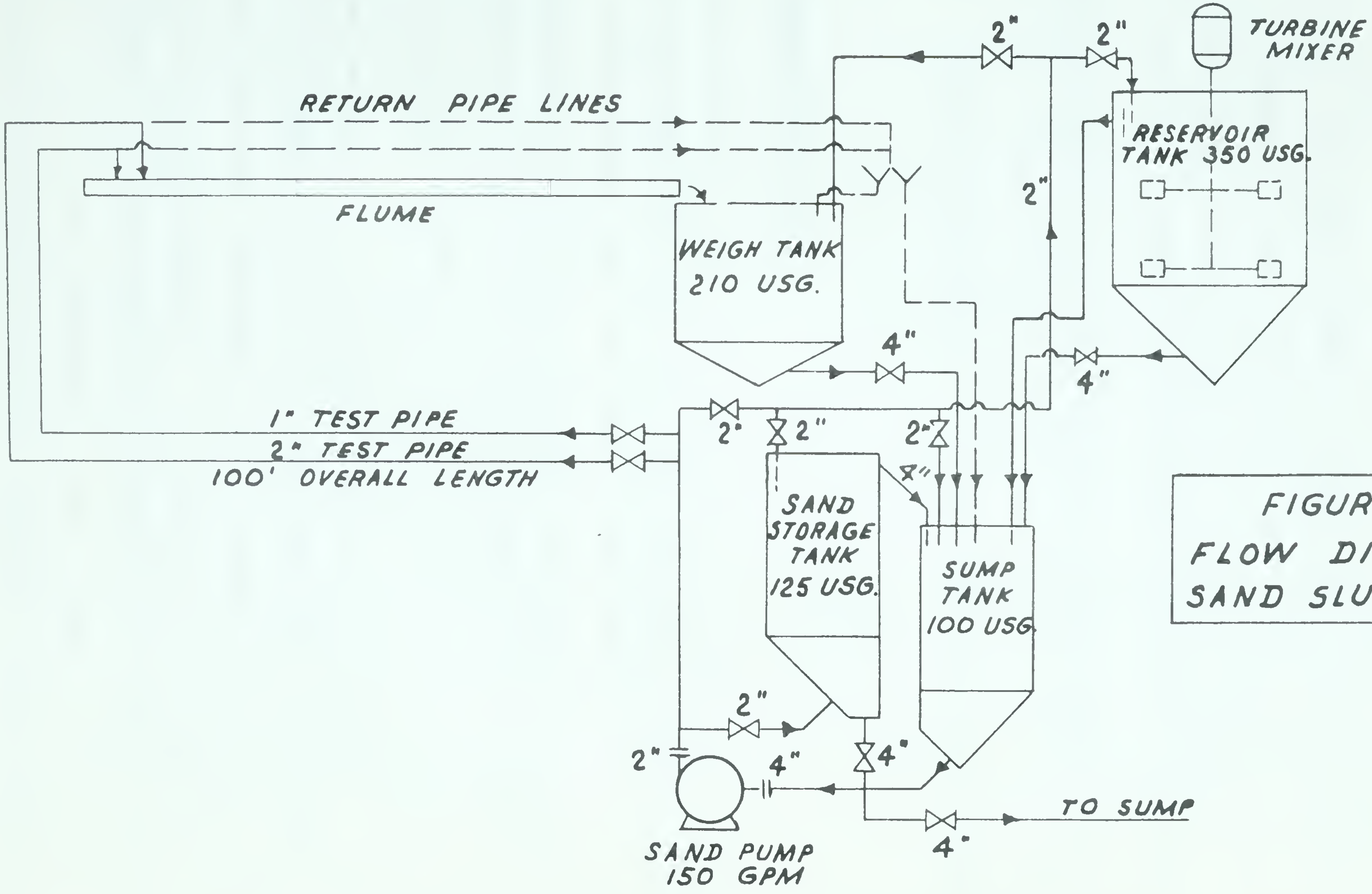


FIGURE 1
FLOW DIAGRAM
SAND SLURRY EQUIPMT.

the discharge of the pump, slurry was added from the reservoir tank. A turbine mixer was provided in the reservoir tank to keep the slurry in it from settling-out on the bottom of the tank, thus reducing the amount of sand in the stream used as makeup to the sump tank. The sand storage tank was included in the system to provide storage for sand which could be added automatically to the pump suction. An elutriation system was included in this tank to separate out the fines from the sand if required.

The interconnected piping shown between the various tanks was incorporated for ease of operation and to provide drainage of these tanks when necessary. A detailed description of the actual apparatus is given below.

Materials Used for Slurry Tests:

As previously stated, the slurries were two- or three-component mixtures made up of sand, water and fines. Water was taken from the available supply in the Hydraulics Laboratory, which was fed directly from the City of Edmonton domestic water supply. This water was kept in the system as long as possible to avoid disposal problems. Makeup water was added to replace the evaporation losses.

The sand was supplied by the sponsor of the research program. It was taken from the tailings dump of a pilot plant operating in the Athabasca tar sands near the town of McMurray, Alberta, placed in barrels and transported to the University Laboratory. Although the sand was supplied at different times over an extended period, the physical characteristics of the material did not alter significantly. Visual inspection and grain-size analyses were carried out at frequent intervals. A typical grain-

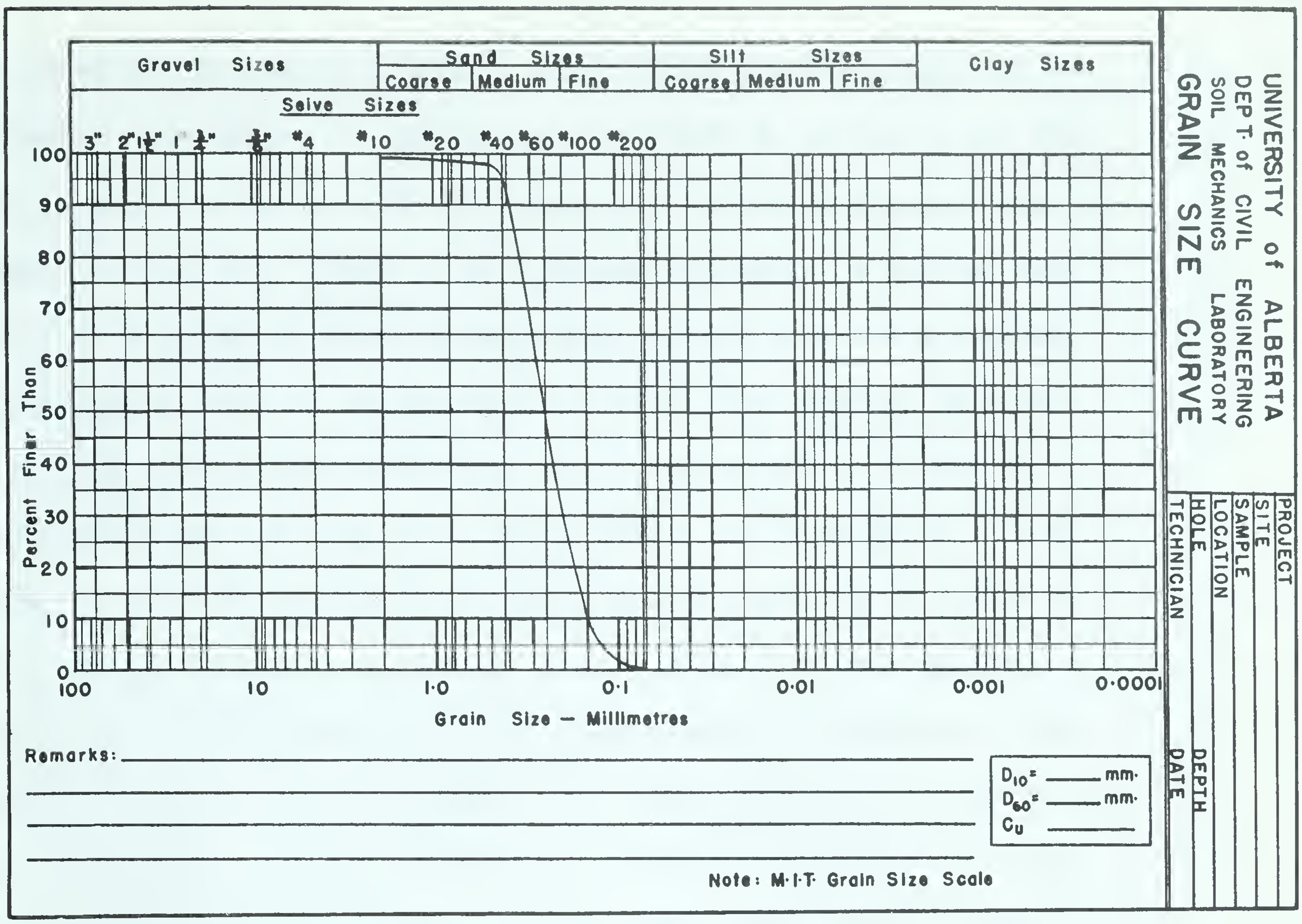


FIGURE 2

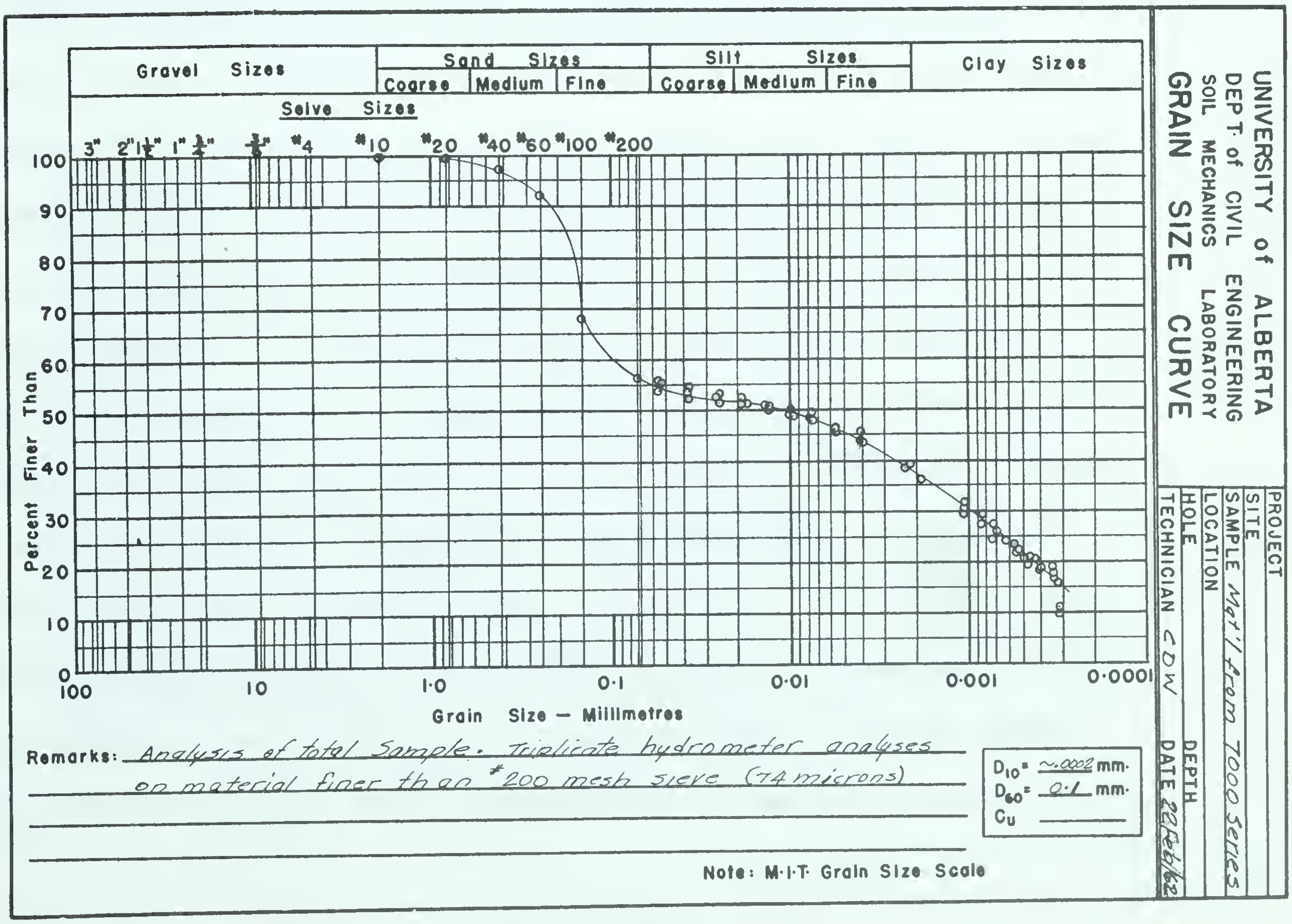


FIGURE 3

size curve can be seen in FIGURE 2, which shows a uniform material in the medium sand range. As can be seen in FIGURE 2, virtually all the material was retained on a N° 200 sieve and the median diameter was 60 mesh, or 0.25 mm. FIGURE 4 is a photomicrograph of a typical sample of the sand, which shows a remarkable uniform size and a rounded to sub-angular shape of the average particle. The material is essentially clean quartz sand with minor discoloration due to traces of bitumen which was not completely extracted in the pilot plant. This bitumen is 8.6° API and therefore has a specific gravity of 1.0099 at 60° F. Since there were very minor traces of this bitumen and the specific gravity was essentially the same as water, its presence was ignored. The grain-size curves were obtained using the A.S.T.M. designation D-422-54T. A.S.T.M. designation D-854-52 tests were performed to determine the specific gravity of the sand, which remained constant at 2.65 during the test program.

The fines slurries were made up from clay obtained from a local ceramics company. The material was purchased in bulk and transported by truck to the University, where it was stored, dry, in barrels. When the material was to be used for slurry preparation, it was pulverized on a vibrating grizzly and introduced into the slurry in one-inch size lumps or smaller. Although the material is referred to as "clay", it had considerable portions outside the clay-size range, with some of it in fact being larger than 200 mesh. This presented no difficulty since the split point between the material called "sand" and the material called "fines" was taken as 200 mesh. The portion of the material taken from the ceramics company which was +200 mesh merely became part of the sand, whereas the minor amount of the sand which was -200 mesh became part of the fines as far as the experimental program was concerned.

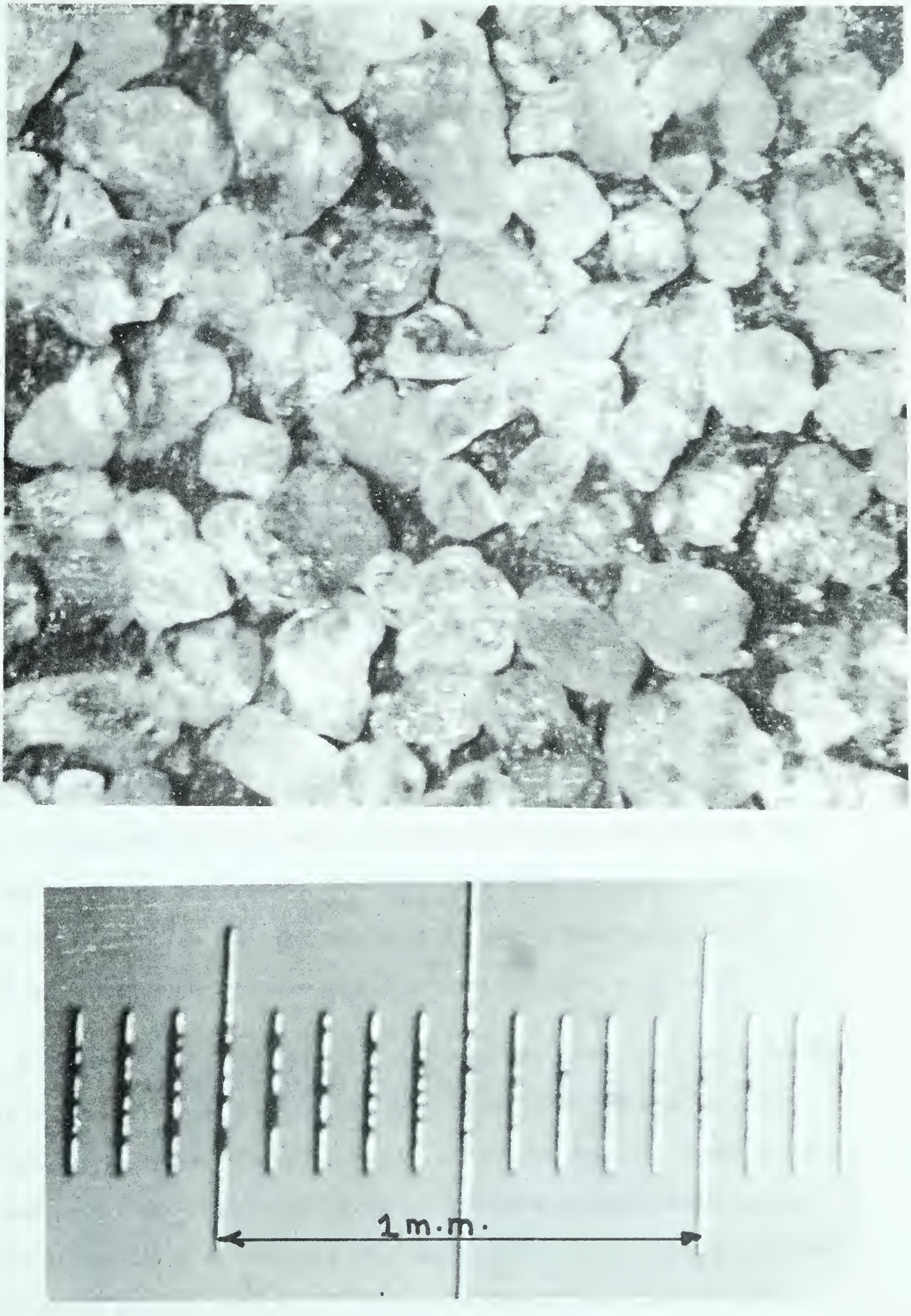


Figure 4. PHOTOMICROGRAPH OF SAND GRAINS.

As already discussed, the material had a fairly wide range of particle size from +200 mesh down to the sub-micron range. Since it was difficult to sample, it was decided to take samples from the slurry test unit and perform grain-size analyses on the total sample of sand plus fines, rather than perform detailed grain-size analyses on the material. A representative analysis for the size distribution can be seen on FIGURE 3. For the particular slurry tested, it can be seen that 44% of the material was sand and 56% was fines. One of the most interesting things shown on FIGURE 3 is the absence of the material in the silt range, particularly for the coarse and medium silt fractions. Over 60% of the fines was in the clay or sub-micron size range.

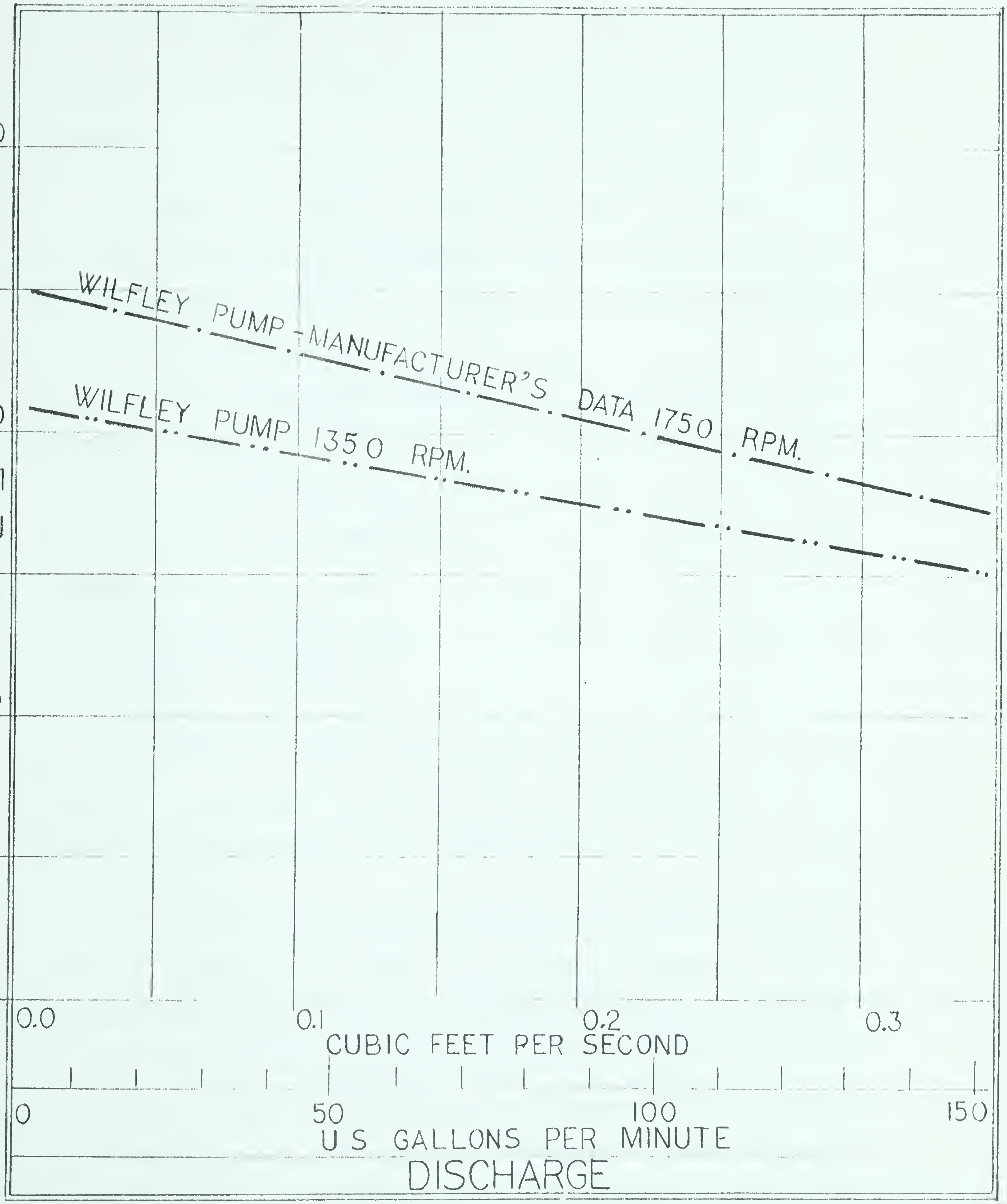
A microscopic and photomicrograph study carried out by the sponsor indicated that the material was predominantly illite and kaolinite.

Experimental Apparatus:

The equipment as originally designed and constructed has been described by Ansley and Hebbert (Ref. 1). The basic apparatus operated quite satisfactorily with the exception of valves and the test pipe section. These were modified as the research program progressed.

A 150 U.S. gpm 4" x 2" Wilfley sand pump was used in the experimental system. It was driven at 1350 rpm by a 10 HP, 1725 RPM electric motor through a V-belt speed-reduction drive. The pump impeller used throughout was a shrouded centrifugal type. During the eighteen-month period of the tests, the pump required only occasional minor servicing to allow for cleaning and the removal of stones and debris from the shrouded

FIGURE 5



CHARACTERISTIC CURVES FOR WILFLEY PUMP.

impeller. A characteristic curve was derived for the pump and is compared with the manufacturer's pump curve in FIGURE 5. The discrepancy between the two curves is due to the lower speed at which the pump was operated.

The capacity of the various tanks can be seen in FIGURE 1. In all cases the tanks were of rectangular steel construction with a converging prismoidal type bottom. In general, the tanks operated quite satisfactorily although there was a tendency for the material to accumulate in the corners of both the weigh tank and the reservoir tank. Construction details of these tanks can be found in Ref. 3. As originally built, throttling was done with rubber pinch valves, but experience with this type of valve showed them to be quite unsatisfactory. Both the weigh tank and the reservoir tank needed to be opened or closed almost instantaneously and 4-inch plug valves were tried in these locations and found quite satisfactory.

The two parallel pipeline test sections were made up of 1" and 2" Schedule 40 steel pipe. The experimental results discussed in this thesis are those taken from the 2" pipe section.

Flow entered this test section 15 feet (90 diameters) downstream from a 90° elbow on the discharge side of the Wilfley pump. Three test sections were connected in series, as shown on FIGURE 6, one of which was 12.0 feet long and having a mean diameter of 0.162 feet, the other two being 20.5 feet long and having a mean diameter of 0.173 feet. At the downstream end of the test line, a transparent plastic section of pipe was included, which can be seen in PLATES I and II. The original observation section did not have the connecting bars between the flanges

FIGURE 5

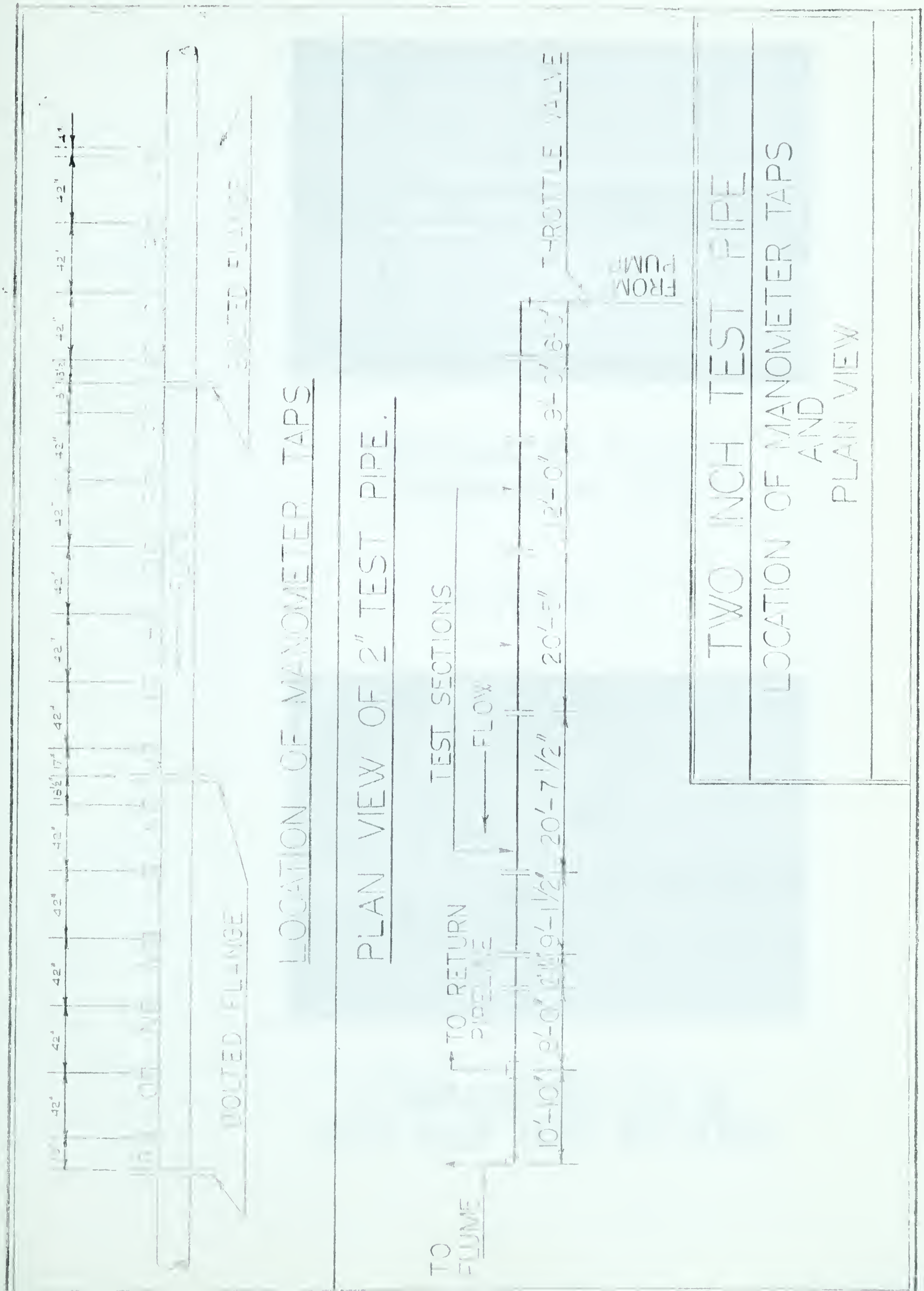
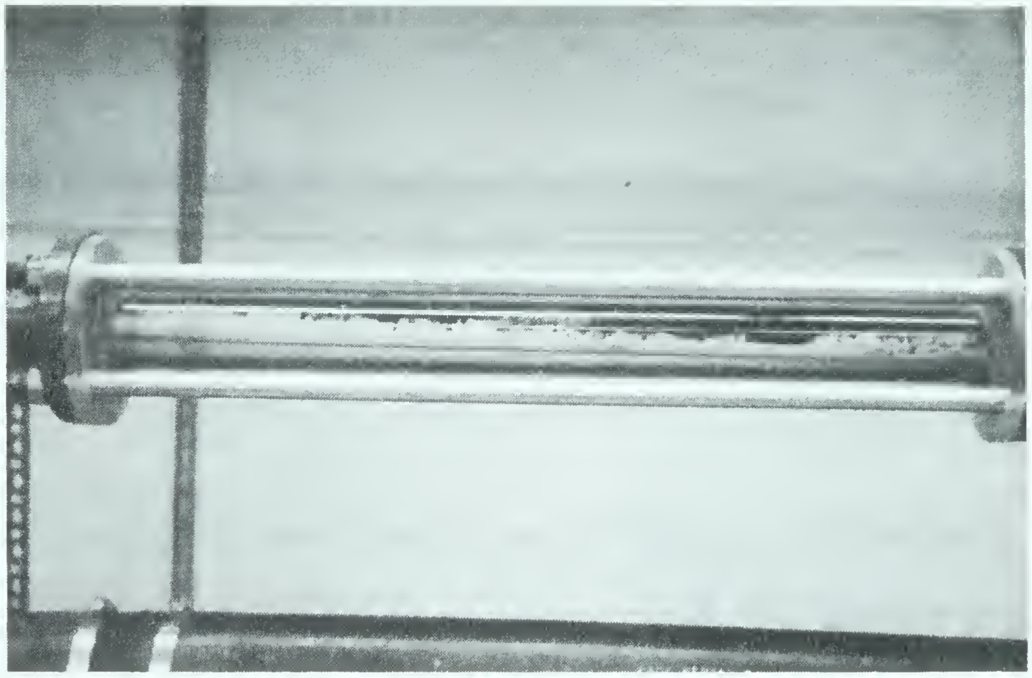

TWO INCH TEST PIPE
LOCATION OF MANOMETER TAPS
AND
PLAN VIEW
LOCATION OF MANOMETER TAPS
PLAN VIEW OF 2" TEST PIPE.
TEST SECTIONS
FLOW
TO RETURN
PIPE LINE
TO
FLUME
FROM
PUMP
BOLTED FLANGE
20'-7 1/2"
20'-5"

PLATE II



TRANSPARENT PLASTIC
OBSERVATION PIPE.

PLATE III

2″ MANOMETER TAP IN
20.5 FOOT TEST SECTIONS

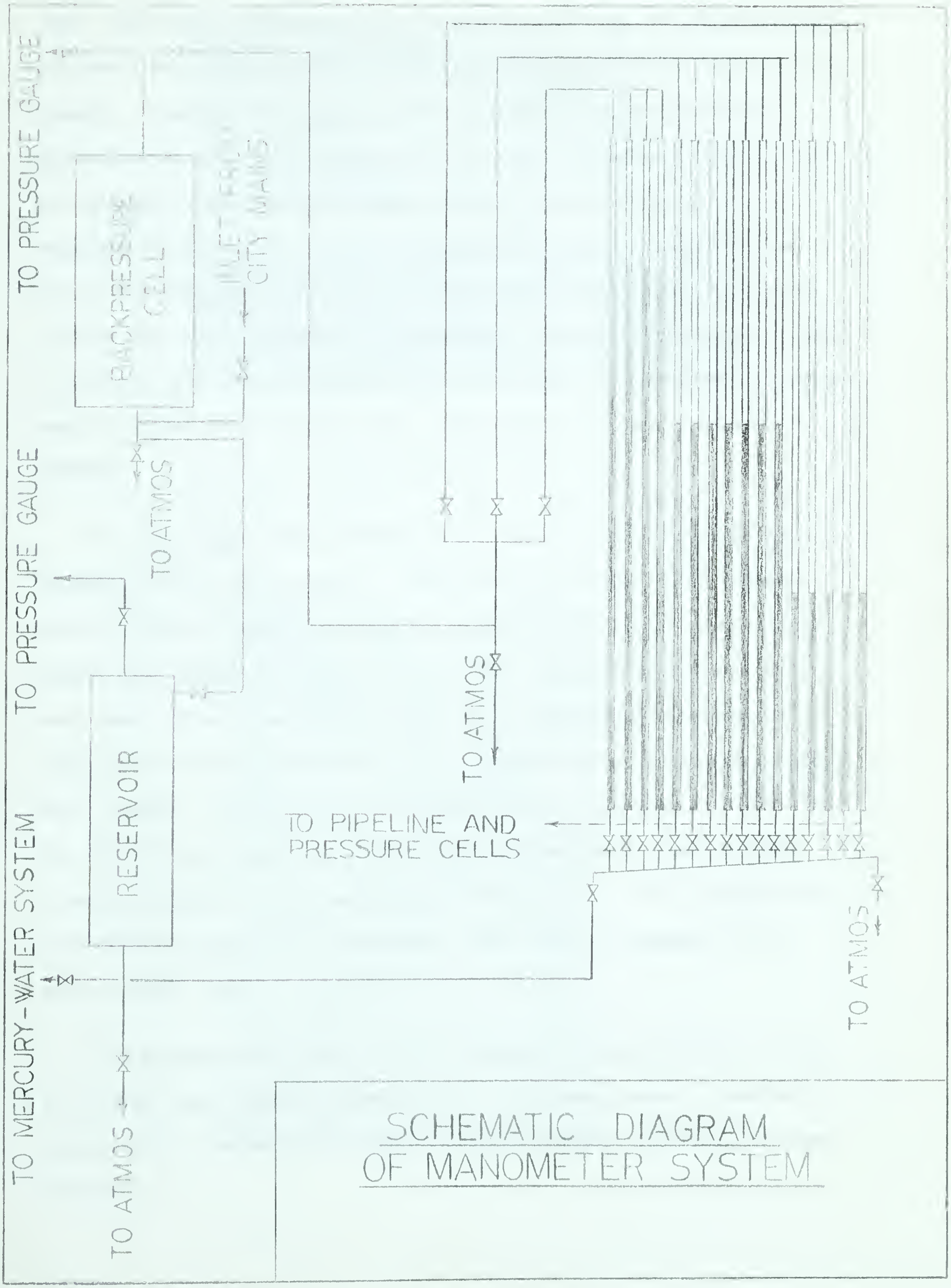
as shown and frequent cracking of the plastic was encountered; but after the bars were added no difficulty of this type was met. The suitability of this section for determining the flow condition in the pipe is clearly shown on PLATE I, where a dune can be seen on the bottom of the pipe.

Instrumentation:

The original instrumentation was described by Ansley and Hebbert (Ref. 1) in some detail. Ansley (Ref. 2) has described the method which was developed to determine the proportions of sand and fines in two and three-component mixtures. In general, the weigh tank and the laboratory method used to evaluate the components of the mixtures has proved quite successful. To check the accuracy of the results and the reproducibility, a detailed test program was run and analysed on a digital computer. This is described in Ref. 3, where it is shown that a series of 40 to 60 controlled tests for different composition slurries indicated an excellent reproducibility of results. However, this was not the case with the pressure drop measuring apparatus originally installed.

The original system was a board fitted with a series of manometers connected through Tygon tubing to manometer taps along the test pipeline. During a run, the manometers were read in order and then the pressure drop calculated. When a series of such pressure drop calculations was carried out on constant operating conditions, great variations in results were found. This was due to two main defects in the system: first, some of the manometers and Tygon tubing became plugged because the solids moved out of the pipeline through the tap into the equipment; secondly, marked

FIGURE 7



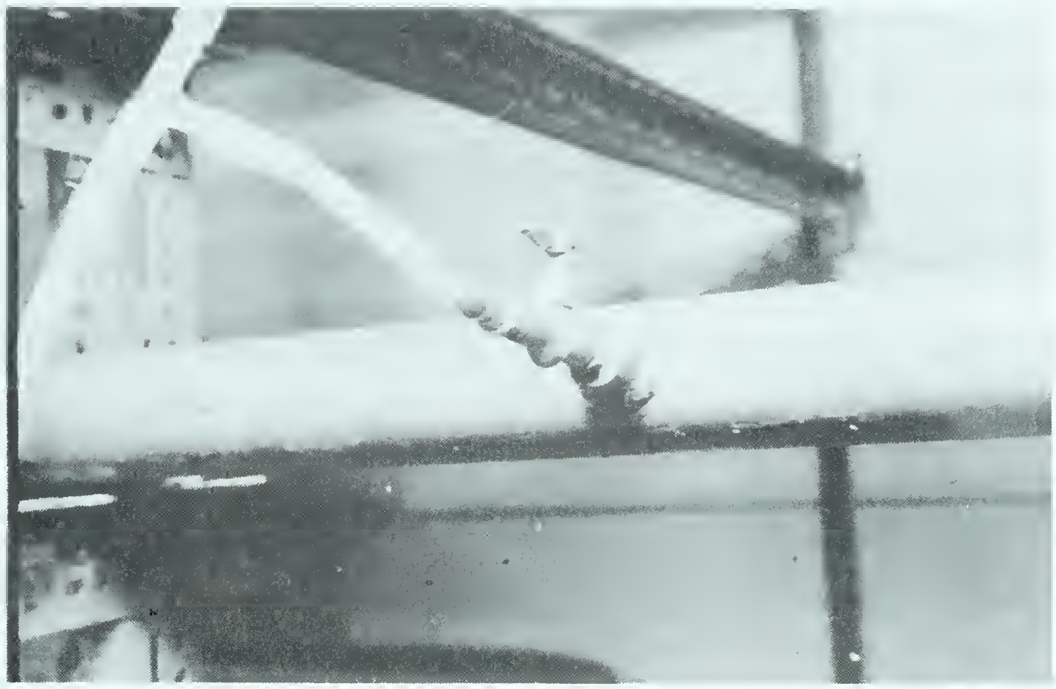
SCHEMATIC DIAGRAM OF MANOMETER SYSTEM

fluctuations were noticed in the manometers, making them difficult to read. The latter difficulty was overcome by mounting the manometers on one board and taking a picture so that the manometers were read simultaneously. However, the plugging of the equipment due to solids was a problem which could not be overcome so simply. From day to day different manometer leads became plugged and could not be freed without disengaging the manometer line and flushing with a high-pressure stream. One of the most difficult parts of this flushing was to actually clean out the tap, which frequently plugged when a sand particle lodged right in its orifice. With these difficulties in mind, a new manometer system was introduced into the apparatus. The system is shown on schematic FIGURE 7.

The two longer test sections were fitted with $\frac{1}{4}$" manometer taps threaded into 2" pipe hangers. These were bolted over 1/16" diameter holes at 42-inch intervals along the pipeline with rubber gaskets and gasket glue employed to ensure a tight fit. Several manometer taps were used, since it was feared that some of them would be plugged at any given time, and a minimum of four would be required to give a reliable reading. A picture of the manometer tap can be seen on PLATE III. The 12-foot test section was fitted with $\frac{1}{4}$" manometer taps threaded directly into $\frac{1}{4}$" nipples welded on to the pipe. A 1/16" diameter hole connected the flow with the manometer tap. This arrangement can be seen on PLATE IV.

The pressure feed lines from the manometer tap were made up using $\frac{1}{4}$" R.3603 Tygon flexible plastic hose. All these pressure leads were supported by a wooden trough hung alongside the test pipeline, as shown on PLATE V.

PLATE IV



2" MANOMETER TAP
IN 12 FOOT TEST SECTION.

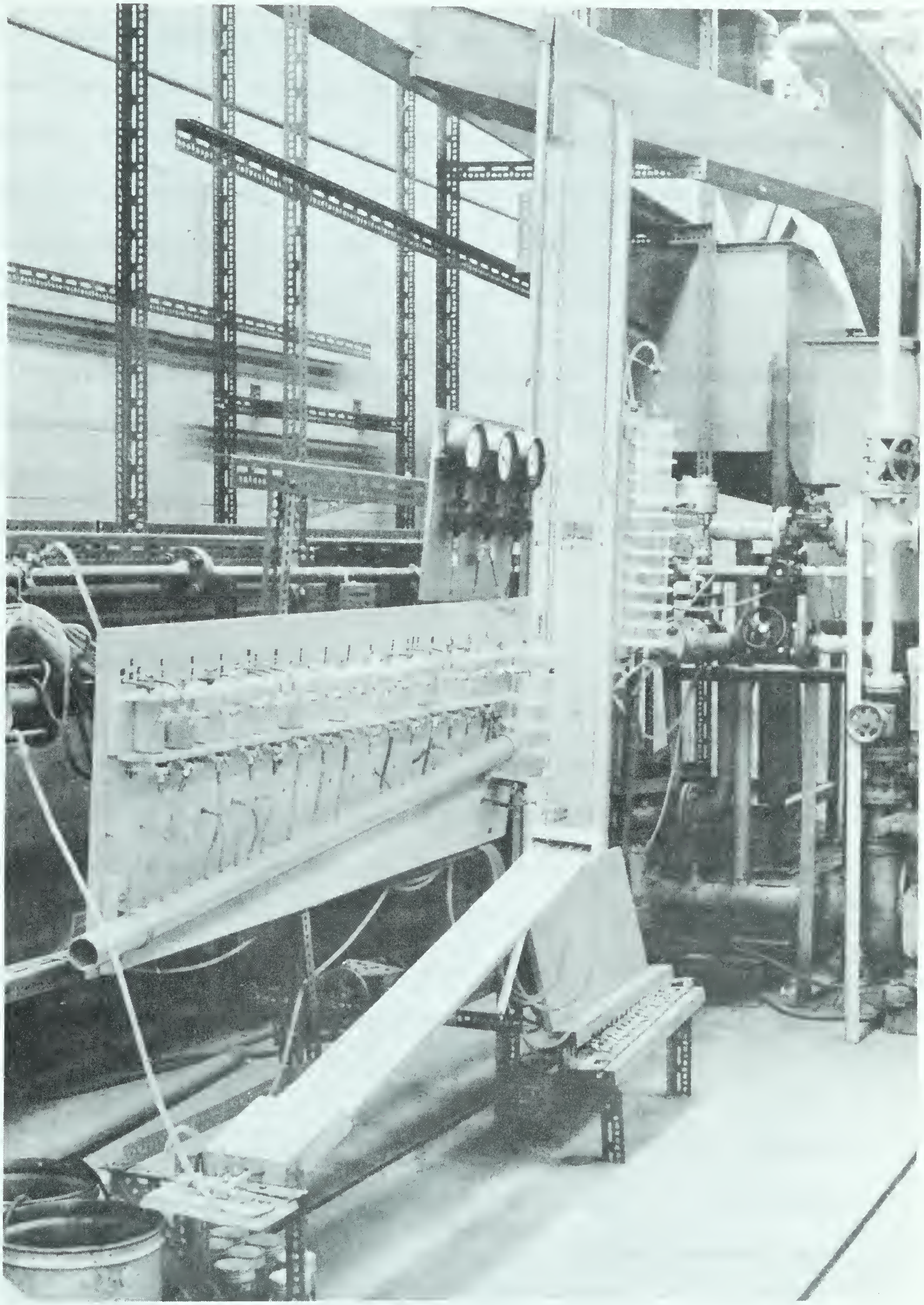
PLATE V

VIEW OF 2"
TEST PIPE

The manometers were arranged in three groups - one from each test section - and mounted on a common board as shown in PLATES VI and XI. The manometers were made up from two 4-foot lengths of $\frac{1}{4}$" diameter glass tubing and connected by short pieces of Tygon hose. Since the pressure drops between the beginning and end of the test sections could be relatively high, it was necessary to be able to back-pressure the manometers themselves to eliminate having extremely long manometer stand-pipes. It was therefore necessary to provide facilities for draining, filling and pressurizing each manometer. Suitable valve installations were made so that each manometer group could be pressurized from a back-pressure cell or de-pressurized to the atmosphere and this procedure could be applied to each group singly or in combination with the other groups. Filling and draining were accomplished through a manifold, which is shown on PLATE VII. The bottom of each manometer connected to a $\frac{1}{4}$" glass tee-section. One branch of the tee transmitted pressure from the pipeline to the manometer; the other branch communicated to the 1" manifold. All sixteen manometers were connected in this way to allow the manifold to act as a common terminal for draining and filling. The manifold was mounted on an incline, as the photograph shows. The drain was at the higher end; the inlet from the reservoir of coloured water at the lower. Since the branching tees from the manometers were inclined downwards into the manifold, filling and draining was accomplished without trapping air.

Since tap water from the City of Edmonton domestic supply was available at a pressure much greater than that encountered in the pipeline, it was decided to use it and to fill and pressurize the manometer system.

PLATE VI



VIEW OF MANOMETER SYSTEM

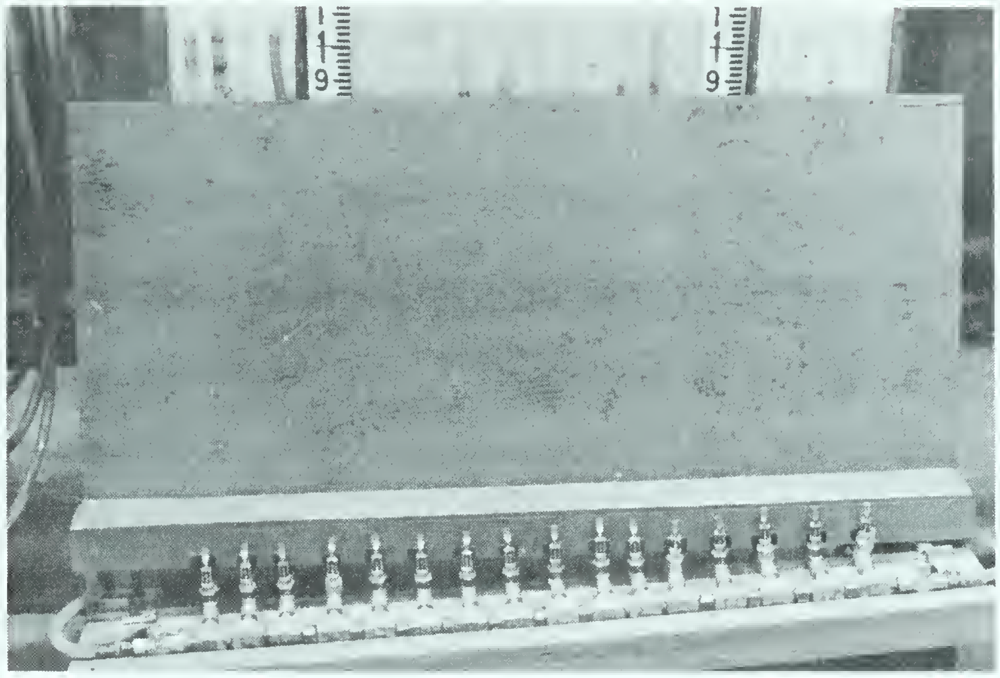
The cylindrical back-pressure cell shown in PLATE VIII was filled from the City supply, causing the air above the water level to compress. In this way, any desired pressure in the range of atmospheric to the City pressure at the tap could be obtained. Suitable valving was arranged whereby this pressure could be directed pneumatically from the top of the back-pressure cell to the top of the air-over-water manometers, or hydraulically to a reservoir cell. A drain was also provided.

The reservoir cell seen in PLATE IX served as a switching point to the pressure gauge and manometers, as well as a receptacle for coloured water. The water was coloured using a standard laboratory reagent called "Fluorescein" giving a greenish colour which showed up quite well in the photographs.

The pressure gauge which can be seen in PLATE VI was used to read the manometer system gauge pressures hydraulically in one-pound increments between zero psi and 60 psi gauge. The other gauge seen in the photograph was used to read the pump discharge pressure. The pressure gauge was used as an aid in applying back-pressure to the manometers and to make sure that pressures were not allowed in any part of the system which would endanger the apparatus. The pressure readings were taken from any part of the instrumentation through the reservoir cell by suitable valving.

To eliminate the problem of the solids collecting in the bottom of the manometer standpipes, sediment traps were included. This provided a definite cut-off point between the slurry section and the water section of the manometer system. The Tygon tubing leading from the manometer tap entered the cell at the bottom through a tee shared with the

PLATE VII



MANOMETER MANIFOLD

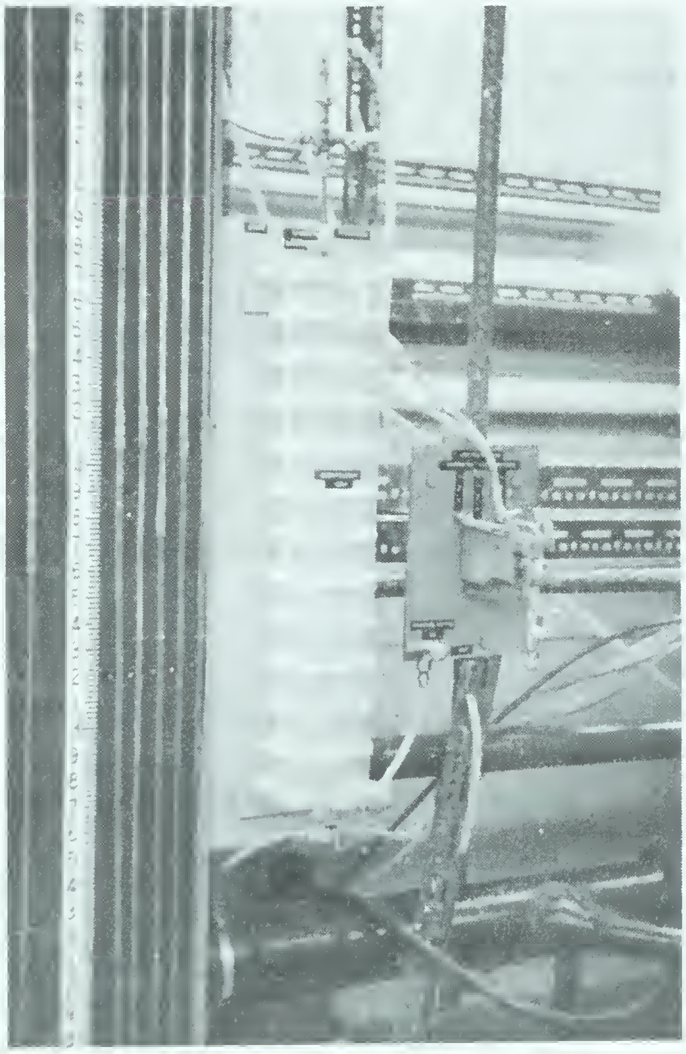


PLATE VIII

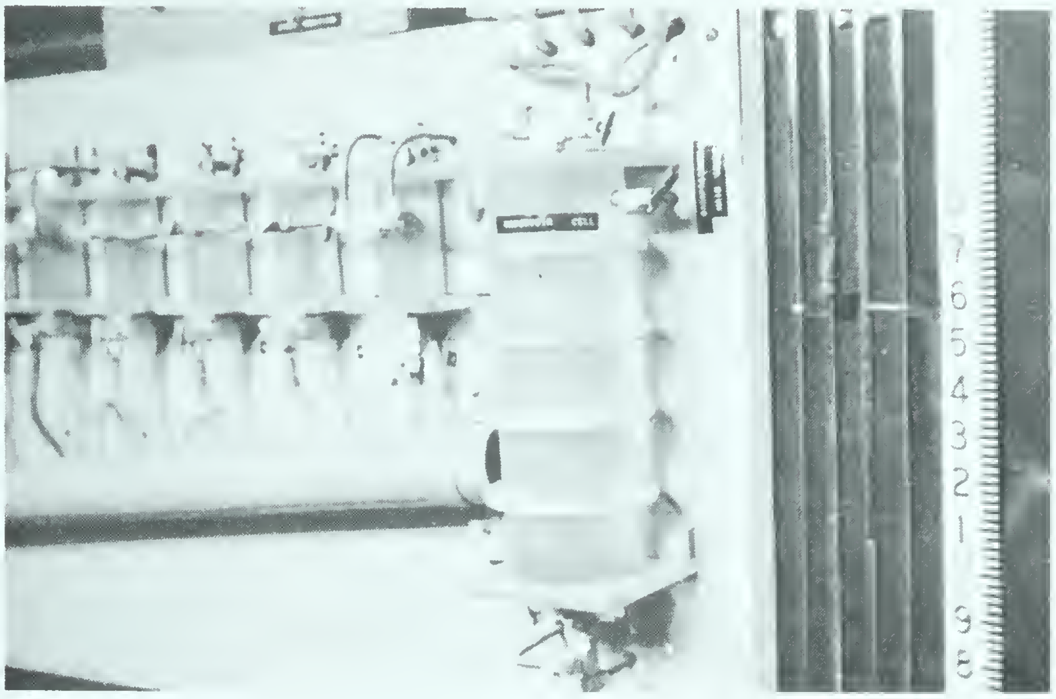
BACK-PRESSURE CELL

sediment drain valve, which was normally closed. The pressure conveyed by this lead line was transmitted to the manometer through a valve mounted two-thirds of the way up the cell. This valve could be throttled to reduce the effect of pipeline pressure surges on the manometer. At the top of the cell an air valve was located which was opened to the atmosphere when it was necessary to release trapped air. All this equipment can be clearly seen on PLATE X. As can be seen in this photograph, considerable solids tended to build up in the bottom of these cells. The drain pipe facilitated removal of these solids.

As previously mentioned, the manometer system became inoperative when solids were trapped either in the small opening in the tap and the lead lines or the manometers themselves. The solids which entered the system collected in the bottom of the sediment traps, thus reducing the plugging problem. If plugging occurred, it was usually cleared effectively by flushing the particular manometer line back into the pipeline using the back-pressure system with clean water. In the event that the orifice at the manometer tap became plugged with sand and the pressure was not sufficient in the back-pressure system to flush it clear, the Tygon lead was removed from the manometer tap and a high-pressure air compressor was attached and the orifice blown clean.

The pressure fluctuations could be reduced using the throttle valves on the sediment traps, thus reducing the oscillations in the manometers themselves. To avoid the fluctuations over a long period of time, the manometers were read simultaneously with a camera. With good photofloodlighting and the green dye in the manometers it was quite simple to take a picture of all the manometers at one time and later read off the

PLATE IX



RESERVOIR CELL.

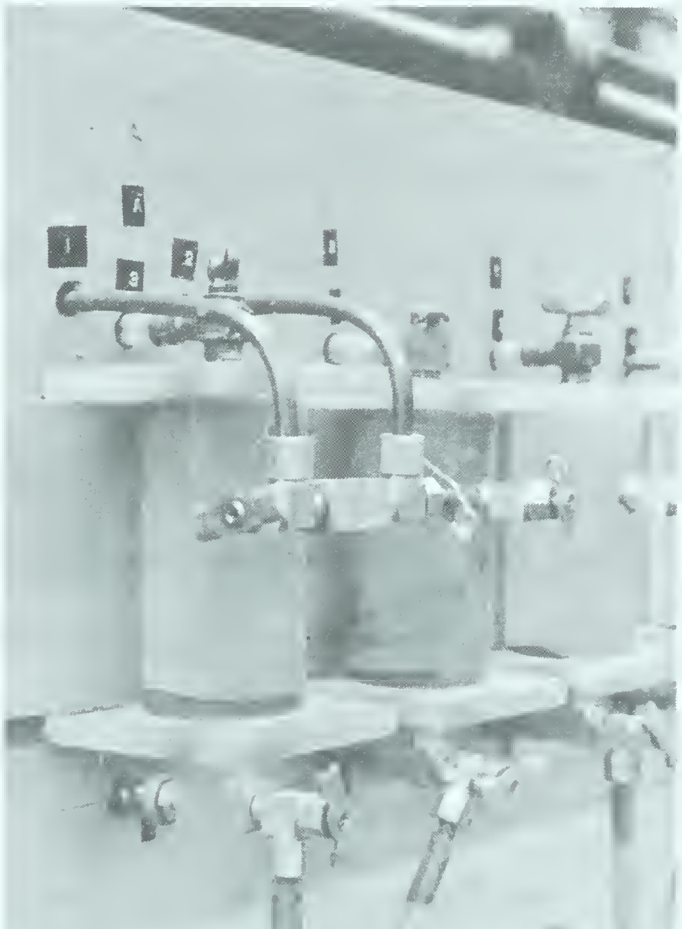


PLATE X
SEDIMENT TRAPS

values. A picture taken during one of the test runs can be seen in PLATE XI. The meniscus is clearly shown and the pressure measurements can be easily read.

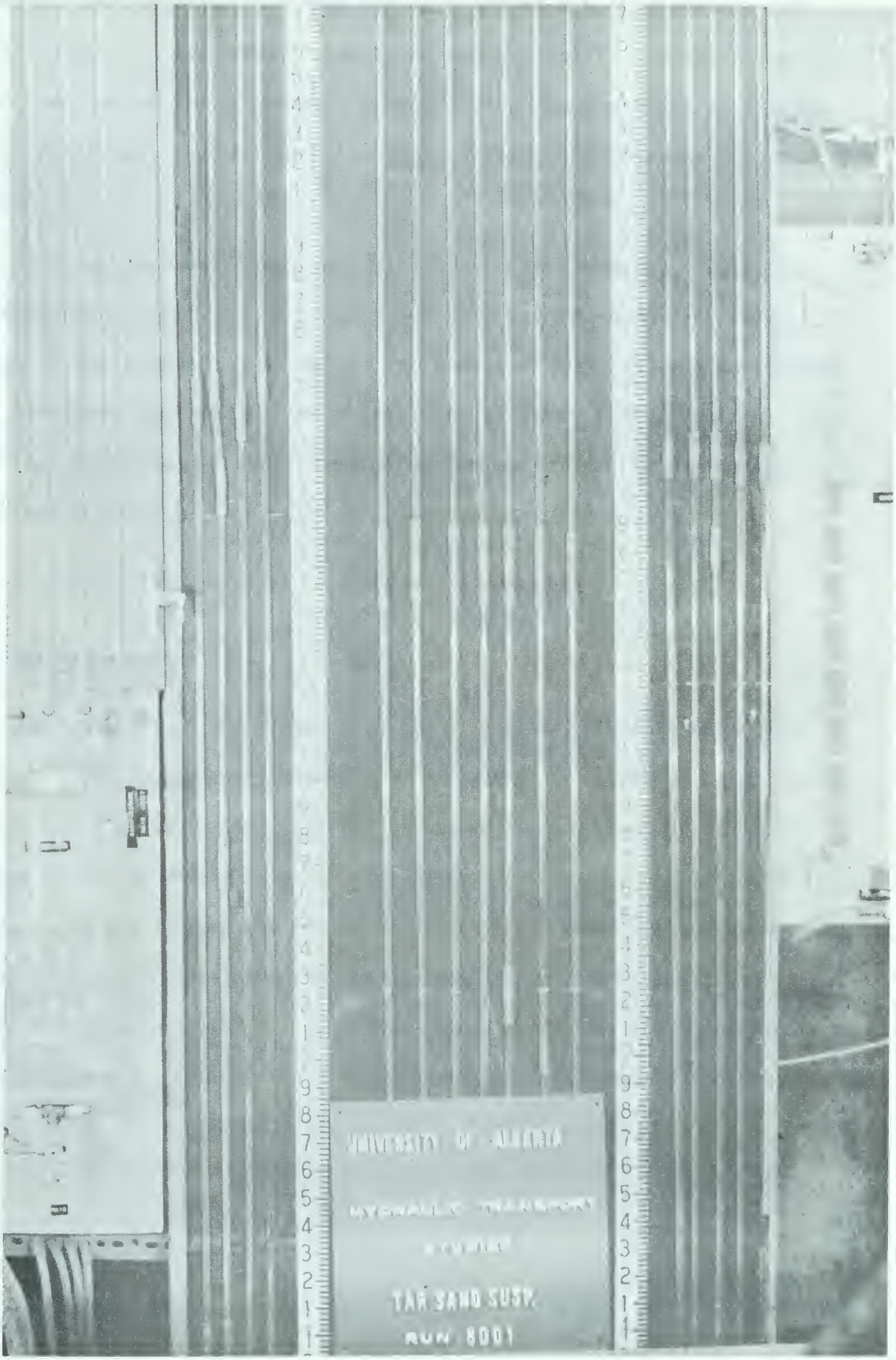
This instrumentation effectively eliminated problems earlier encountered in the research program. The complex valving system presented operational difficulty at first, but through familiarity with the system this became negligible.

Experimental Procedure:

A slurry of fines was built up over a period of time until the material was considered a fully homogeneous mixture. Since the material was all stored in either the weigh tank or the reservoir tank at the end of a day's run, the water losses due to evaporation could be made up before the runs were recommenced. This ensured that the concentration of fines in the slurry remained approximately constant at the desired level. Sand was added in varying amounts as desired. This material was usually shovelled directly into the sump tank or at times added through the sand-storage tank.

The discharge variations had little or no effect on the concentration of fines in the system, since it was considered a homogeneous mixture. However, there was an appreciable change in the amount of sand transported since at low discharges the material tended to hang up in the sump tank or weigh tank. This condition dictated the type of test program adopted. A series of tests was run at approximately constant fines concentration while variations in discharge determined the amount of sand transported.

PLATE XI



TEST RUN MANOMETER READINGS.

Normally, the operation followed was to start at a high discharge and throttle-back until a dune or bed condition was noticed in the transparent section of the pipeline. Pressure drop readings were at thirty-minute intervals, to make sure that equilibrium conditions had been reached.

Grab samples were taken in duplicate and were analysed in the manner described in Ref. 2. A picture was taken of the manometer board to record the pressure drop data. The number of the test run was posted on a board and included in the photograph for later identification. The discharge measurements were taken using the weigh tank in the method described in Ref. 1.

Accuracy of Results:

The results for the pressure drops at a given velocity show wide scatter. This has been reported by other workers (Ref. 5). Large fluctuations in the manometer readings indicated the presence of constant surging in the system. This surging became more pronounced at low discharge rates and higher concentration of solids. A complete discussion of the accuracy of the discharge measurements and the composition of the slurry are given in Ref. 3. This discussion shows the discharge measurements accurate to plus or minus 0.005 cubic feet per second and the volume concentration of solids accurate to plus or minus 0.5%.

CHAPTER III

THEORY

Durand (Ref. 6) and Newitt et al (Ref. 7) have each put forward theories to explain the head loss - velocity relationship for mixtures of solids and fluids in circular pipes. Durand classified these mixtures as -

(i) Homogeneous mixtures, where the solids are up to 20 or 30 microns in diameter;

(ii) Intermediate mixtures, where the solids are between 25 and 50 microns in diameter. This is a transition category;

(iii) Heterogeneous mixtures,

a) Heterogeneous mixtures transported in suspension, diameters from 50 to 200 microns,

b) Transition category, diameters 0.2 mm. to 2.0 mm.,

c) Heterogeneous mixtures transported by saltation, diameters above 2 mm.

The size ranges given by Durand are somewhat arbitrary, in that the upper sizes in categories (i) and (ii) depend to some extent on flow velocity.

This study is concerned with homogeneous mixtures, heterogeneous mixtures and the two together.

Homogeneous Mixtures:

Homogeneous mixtures are Bingham plastics and so cannot be compared with pure liquids in the laminar flow regime. In the turbulent flow regime, however, the Darcy-Weisbach friction factors for water and homogeneous mixtures are substantially the same (Ref. 6, page 8). The hydraulic gradient for a mixture can thus be expressed as -

$$i_m = \frac{\rho_m}{\rho_w} i_w \quad \ldots\ldots (1)$$

provided,

$$f_m = f_w \quad \ldots\ldots (2)$$

The density of a fines-water mixture is -

$$\rho_{f,w} = \rho_w + C_f (\rho_f - \rho_w) \quad \ldots\ldots (3)$$

where the subscripts f refer to the fine material, in this case clay. Equations (1) and (3) can be rearranged to give -

$$\frac{i_{fw} - i_w}{C_f i_w} = \frac{\rho_f}{\rho_w} - 1 \quad \ldots\ldots (4)$$

Equation (4), given by Newitt in Ref. 7, shows that the increase in losses in a pipe due to the presence of clay varies with the square of the flow velocity.

Heterogeneous Mixtures:

Heterogeneous mixtures can only exist in turbulent flow and here the concentration of solids decreases with distance above the bed. Both Durand and Newitt give expressions for increase in slope of the hydraulic grade line due to solids in heterogeneous suspension.

Durand's expression was found by plotting experimental results while Newitt's expression was found as follows:

The volume ($\mathcal{V}$) travels unit length in the time 1/V, and the work performed by the particles on the fluid in this time is -

$$\frac{WK_1}{V} \left[C_s \mathcal{V} (\rho_s - \rho_w) g\right] \quad \ldots\ldots \quad (5)$$

where K_1 is a constant which allows to some extent for the effect of concentration on falling velocity. It is assumed that the particles will tend to fall at a rate proportional to their terminal velocity.

The work done on the particles in the time interval 1/V is -

$$(j_{sw} - j_w)\, \mathcal{V} \rho_{sw}\, g = (i_{sw} - i_w)\, \mathcal{V} \rho_w\, g$$

where the bracketed terms represent the increase in slope of the hydraulic grade line due to the presence of solids. Equating the expressions for work -

$$(i_{sw} - i_w)\, \mathcal{V} \rho_w\, g = \frac{WK_1}{V} \left[C_s \mathcal{V} (\rho_s - \rho_w) g\right]$$

or -

$$i_{sw} - i_w = \frac{WK_1 C_s}{V} \left(\frac{\rho_s}{\rho_w} - 1\right) \quad \ldots\ldots \quad (6)$$

This can be written -

$$\frac{i_{sw} - i_w}{C_s\, i_w} = \frac{2g K_1 DW}{f_w V^3} \left(\frac{\rho_s}{\rho_w} - 1\right) \quad \ldots\ldots \quad (7)$$

Equation (6) shows that the energy loss due to the presence of the solids in heterogeneous suspension varies inversely as the velocity. Unlike the homogeneous case, the presence of solids has a progressively smaller effect on energy loss as velocity increases.

Fines in Sand-Water Mixtures:

By assuming that a homogeneous mixture of fines in water behaves as a true fluid with respect to coarse grains in heterogeneous suspension, it is possible to apply Equations (6) and (7) to the three-phase problem.

Equation (7) gives -

$$\frac{i_{fsw} - i_{fw}}{C_s i_{fw}} = \frac{2g K_1 D W_f}{f_{fw} V^3} \left(\frac{\rho_s}{\rho_{fw}} - 1 \right) \qquad \text{(8)}$$

The fall velocity of particles which obey Stokes' law varies directly with the buoyant weight, or -

$$W_f = W \frac{(\rho_s / \rho_{fw} - 1)}{(\rho_s / \rho_w - 1)}$$

also -

$$f_{fw} = f_w$$

Equation (4) can be written -

$$i_{fw} = i_w \left[\left(\frac{\rho_f}{\rho_w} - 1 \right) C_f^1 + 1 \right]$$

where C_f^1 represents the concentration of fines in the fines-water mixture only.

Equation (8) becomes -

$$\frac{i_{fsw} - i_{fw}}{C_s i_{fw}} = \frac{2g K_1 D W}{f_w V^3} \left(\frac{\rho_s}{\rho_w} - 1 \right) \left(\frac{\rho_s / \rho_{fw} - 1}{\rho_s / \rho_w - 1} \right)^2$$

$$= \frac{i_{sw} - i_w}{C_s i_w} \left(\frac{\rho_s - \rho_{fw}}{\rho_s - \rho_w} \right)^2 \left(\frac{\rho_w}{\rho_{fw}} \right)^2$$

Thus -

$$\frac{i_{fsw} - i_w}{i_{sw} - i_w} = \left(\frac{\rho_s - \rho_{fw}}{\rho_s - \rho_w} \right)^2 \left(\frac{\rho_w}{\rho_{fw}} \right)^2 \left[\left(\frac{\rho_f}{\rho_w} - 1 \right) C_f^1 + 1 \right] + \left[\frac{f V^3 C_f^1}{2gDWK_1 C_s} \right] \left[\frac{(\rho_f - \rho_w)}{(\rho_s - \rho_w)} \right] \qquad \text{(9)}$$

For a typical case -

$$\rho_f = 2.72 \times \frac{62.4}{32.2} = 5.27 \quad \text{slugs/ft.}^3$$

$$\rho_s = 2.65 \times \frac{62.4}{32.2} = 5.14 \quad \text{slugs/ft.}^3$$

$$C_f = 0.10 \quad C_s = 0.10$$

Then -

$$C_f^1 \doteq \frac{C_f}{1-C_s} = \frac{0.10}{0.90} = \underline{\underline{0.111}}$$

$$\rho_{fw} = \rho_w \ (1 - C_f^1) + C_f^1 \times \rho_f$$

$$\rho_{fw} = 1.935\ (1 - 0.111) + (0.111)(5.27)$$

$$\rho_{fw} = 1.721 + 0.586 = 2.307$$

$$\frac{i_{fsw} - i_w}{i_{sw} - i_w} = 0.66 + \frac{1.16\ f\ V^3}{2g\ DWK} \quad \text{.......................} \quad (10)$$

Equations (9) and (10) show that the presence of fines in a heterogeneous suspension will tend to decrease the energy loss at low flow velocities. At high flow velocities the reverse is true.

Equation (9) applies only to turbulent flow, since the homogeneous mixture of fines and water cannot exist under laminar conditions. The settling of particles in the heterogeneous suspension is assumed to follow Stokes' Law, however.

CHAPTER IV

DISCUSSION OF RESULTS

Clear Water Tests:

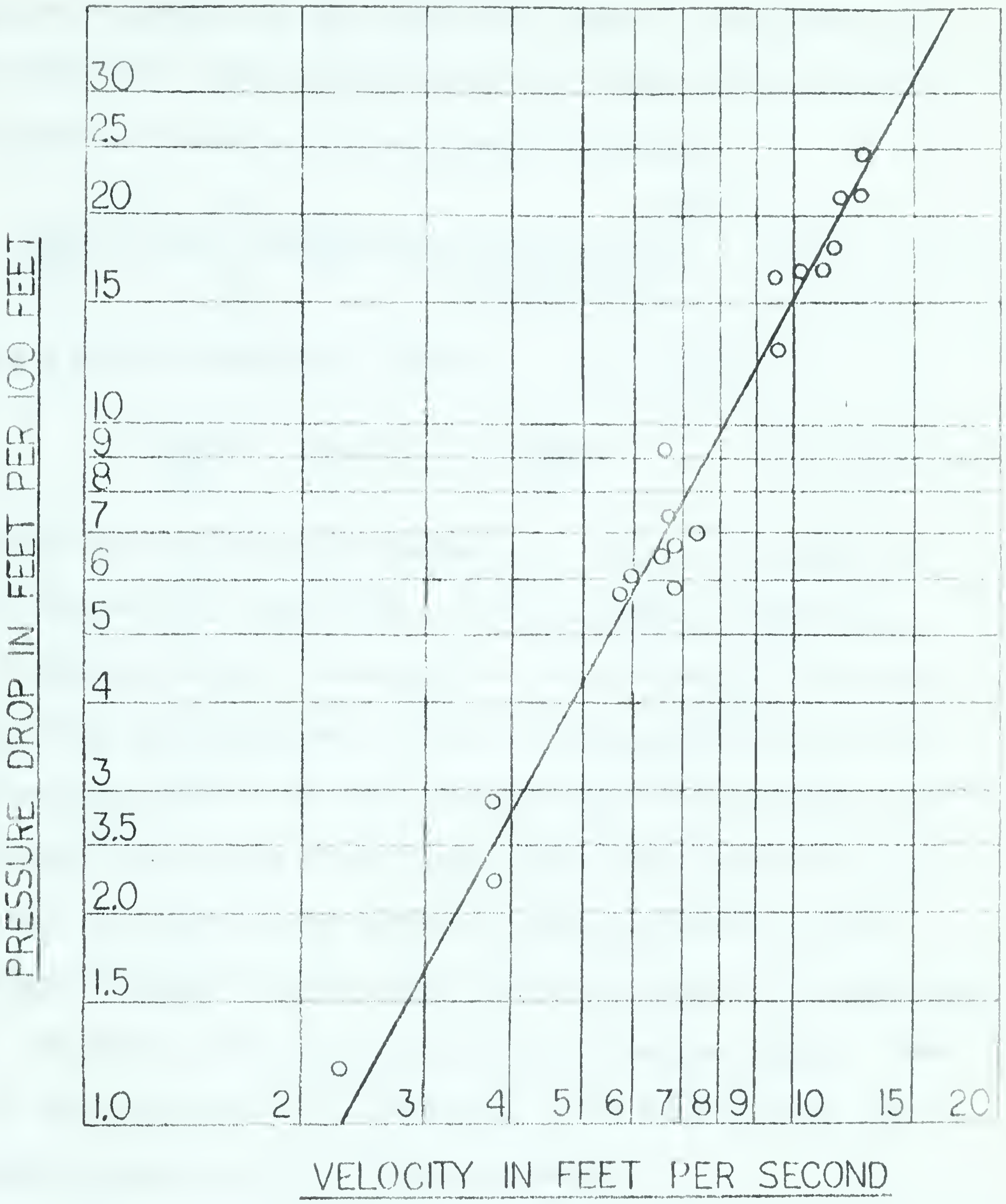
Clear water tests were run at the beginning of the program to establish the characteristics of the pipeline. These tests were repeated at regular intervals throughout the program to investigate the possibility of erosion on the inside of the pipeline causing changes or a bias in the readings. During the course of the investigation, some seventy clear water tests were carried out.

The clear water data fell on the smooth boundary line of the Moody diagram in the interval of Reynolds' number between 30,000 and 200,000. FIGURE 8 shows these data plotted on log-log coordinates. The range of data shown covers the complete range of discharges available with the pump. This curve was used as the basis for putting the clear water line on all subsequent figures.

Sand-Water Tests:

The next sequence of tests was performed on sand-water slurries of varying concentrations of sand. Much of this work was done by Professor R. H. B. Hebbert during the summer of 1960, using the apparatus as it was originally designed. Hebbert summarized his findings in an unpublished report (Ref. 4) and these data were used to augment those collected by the author. In all, some 150 sand-water tests were conducted.

FIGURE 8



PRESSURE DROP VS VELOCITY FOR CLEAR WATER IN TWO INCH PIPE.

The test data were compared to those of other workers. The two approaches which seemed most applicable were those of Durand (Ref. 6) and Newitt (Ref. 7). After extensive testing, Durand put forth the following empirical relation for solids-water slurries:

$$\frac{\dot{i} - \dot{i}_w}{C\dot{i}_w} = 176 \left[\frac{gD\,(s - 1)}{V^2} \; \frac{W}{\sqrt{gd\,(s - 1)}} \right]^{1.5} \qquad \text{(11)}$$

Newitt gave a similar expression based on far less testing:

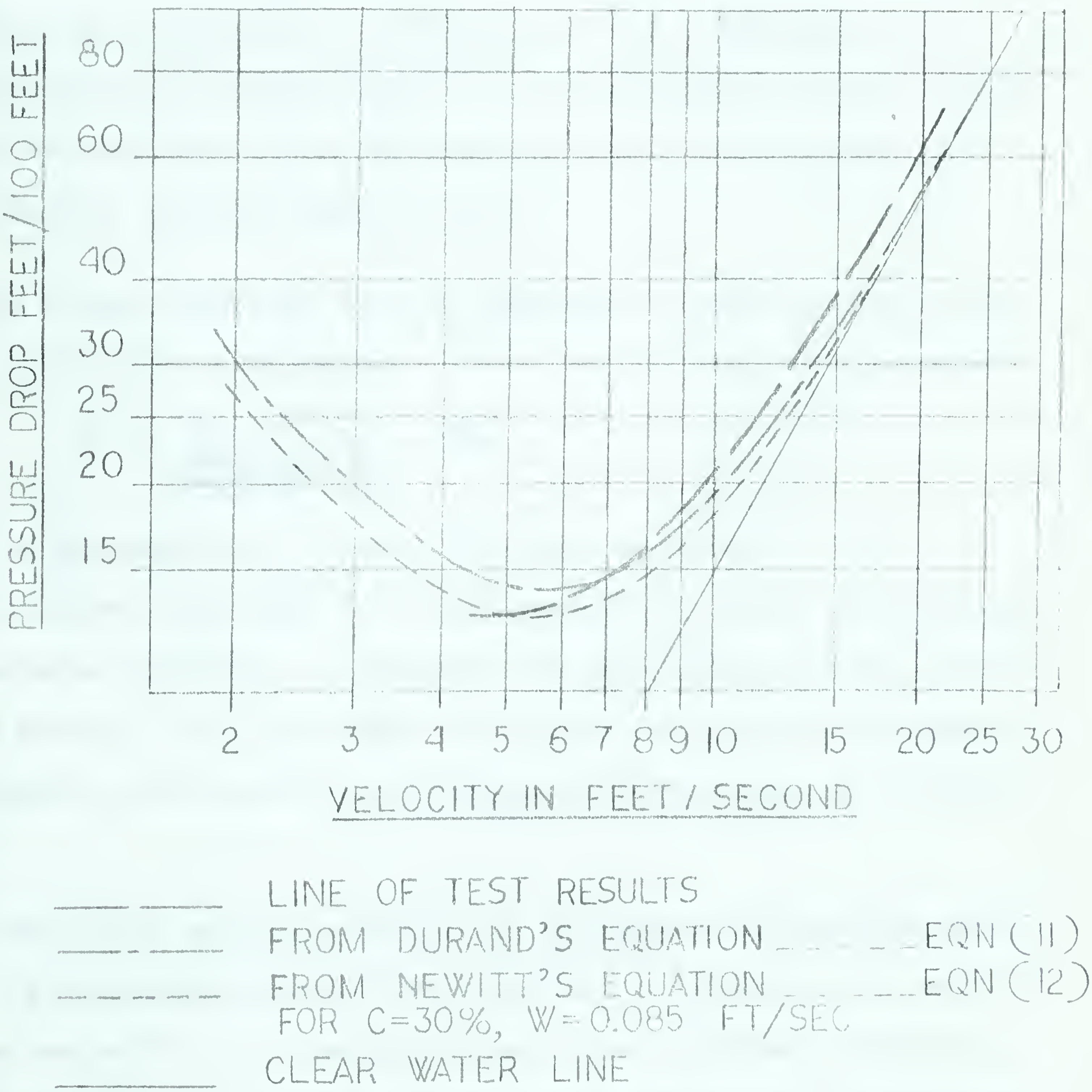
$$\frac{\dot{i} - \dot{i}_w}{C\dot{i}_w} = 1100\,(s - 1)\,\frac{W\,g\,D}{V^3} \qquad \text{(12)}$$

It should be noted that both expressions include W, the settling velocity of the solids. Durand (Ref. 6) has discussed the settling velocity of sand particles in some detail. The sand used in the tests at the University of Alberta were .25 mm. in diameter and lie just outside the limits of Stokes' law. Both Durand (Ref. 6) and Worster (Ref. 5) have shown empirical results of settling rates in this range and a settling velocity of 0.085 feet per second for sand of 0.25 mm. is predicted using an average of values taken from their curves. Extrapolation of Stokes' law shows a settling velocity of 0.14 feet per second. Some preliminary settling tests on the sand used in the Alberta tests indicated a settling velocity of 0.127 feet per second.

FIGURE 9 shows a comparison of test data to the above equations for a sand of 2.65 specific gravity, 0.25 mm. diameter, a settling velocity of 0.085 feet per second, a slurry concentration of 30% sand by volume and a 2-inch diameter pipe.

The test data agree quite satisfactorily with the equations at lower velocities, but do not approach the clear water line assymptotically as the velocity increases. However, from the figure it can be

FIGURE 9



COMPARISON OF DATA
TO PUBLISHED CORRELATIONS.

concluded that Durand's equation is applicable. This is fortunate in that Durand's testing covered a range of 1.5-inch diameter pipes to 29-inch diameter pipes and solids of different sizes and specific gravities for concentrations from 0% to 38% by volume.

A comparative plot is shown on FIG. 10 which demonstrates the sensitivity of the correlations to settling velocity W. The upper line is Durand's equation (12) calculated for a settling velocity of 0.14 feet per second and the lower line is that calculated for a settling velocity of 0.085 feet per second as shown on FIG. 9.

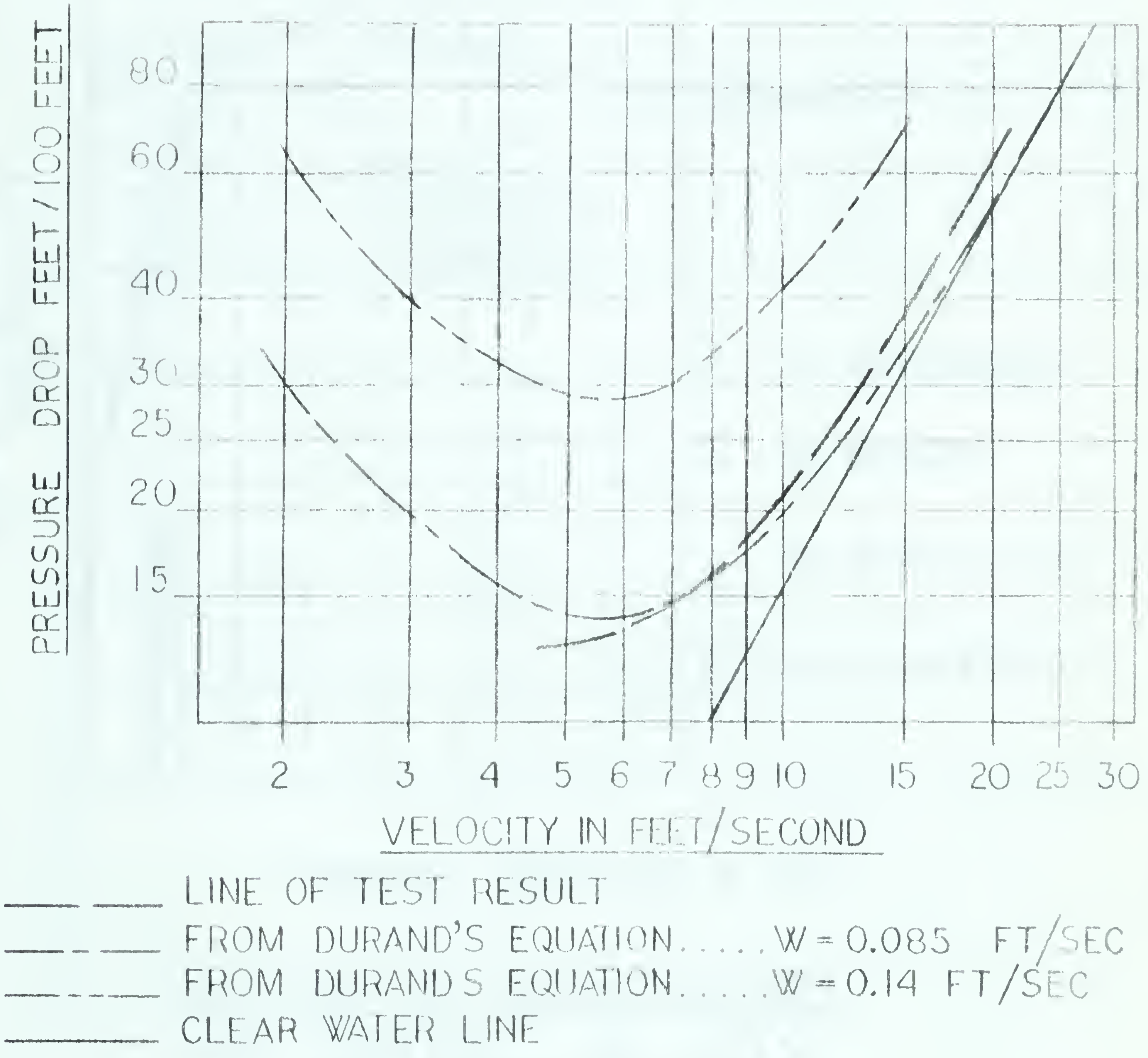
As already discussed, there are advantages to operating the pipeline at as low a velocity as possible. Durand (Ref. 6) developed a parameter:

$$F_L = \frac{V_c}{\sqrt{2gD(s-1)}} = \phi_d \quad \text{.................................} \quad (13)$$

which he expressed as a function of the particle diameter. FIG. 11 is taken from Ref. 6 and shows this relationship for different concentrations of sand-water slurries. For reference, the sand particle diameter of 0.25 mm. is marked. This figure shows that the critical velocity is markedly influenced by the concentration of solids in the size range of the Alberta sand.

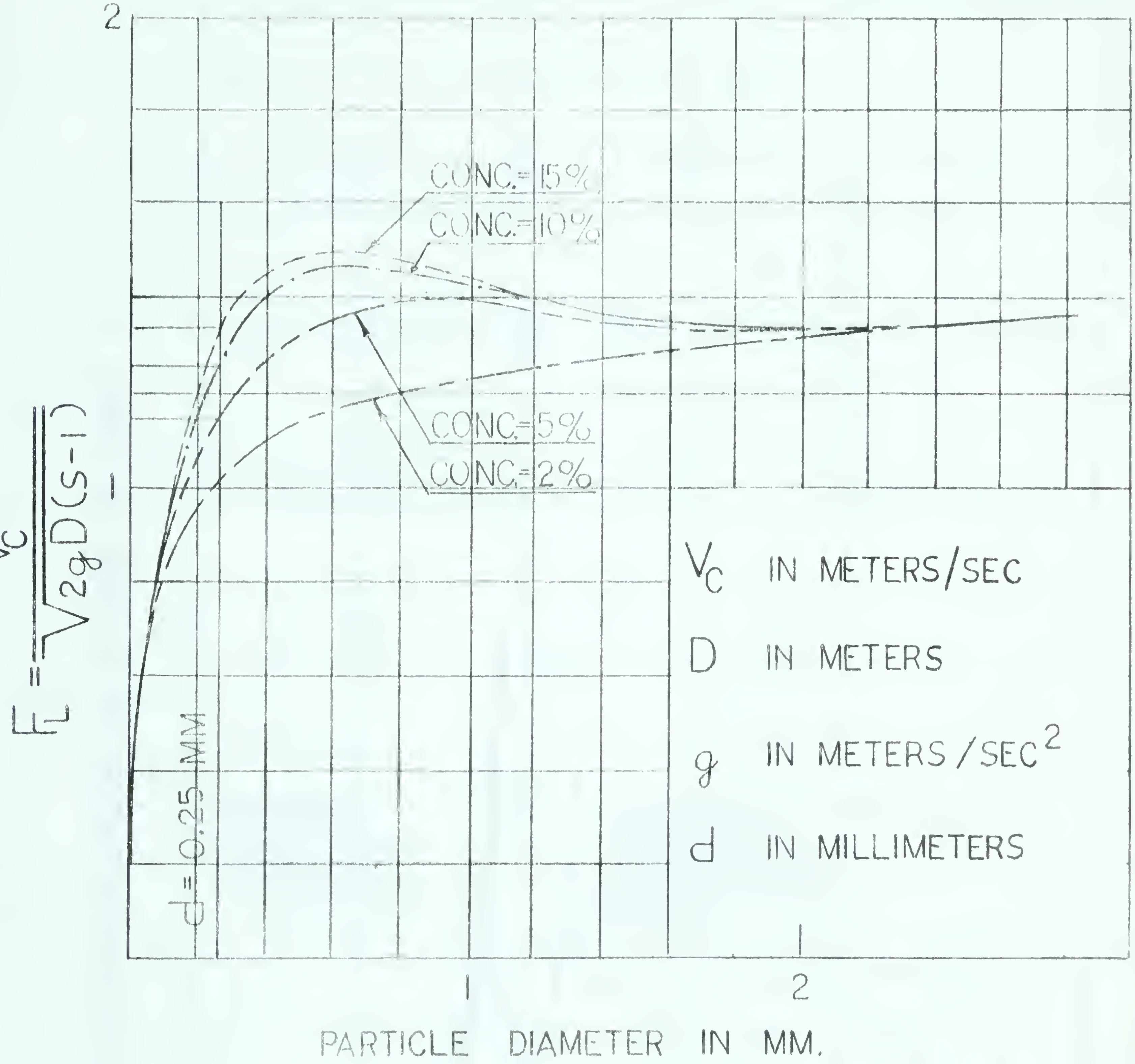
The critical velocity equation (13) as predicted by Durand was compared to the test data taken at the University of Alberta. This comparison can be seen on FIG. 12, in which the heavy curve is Durand's correlation. Several points to the right of this curve show deposition in the pipeline at velocities greater than the Durand critical velocity. The University of Alberta data indicate that a better relation can be expressed using FIG. 11 and -

FIGURE 10



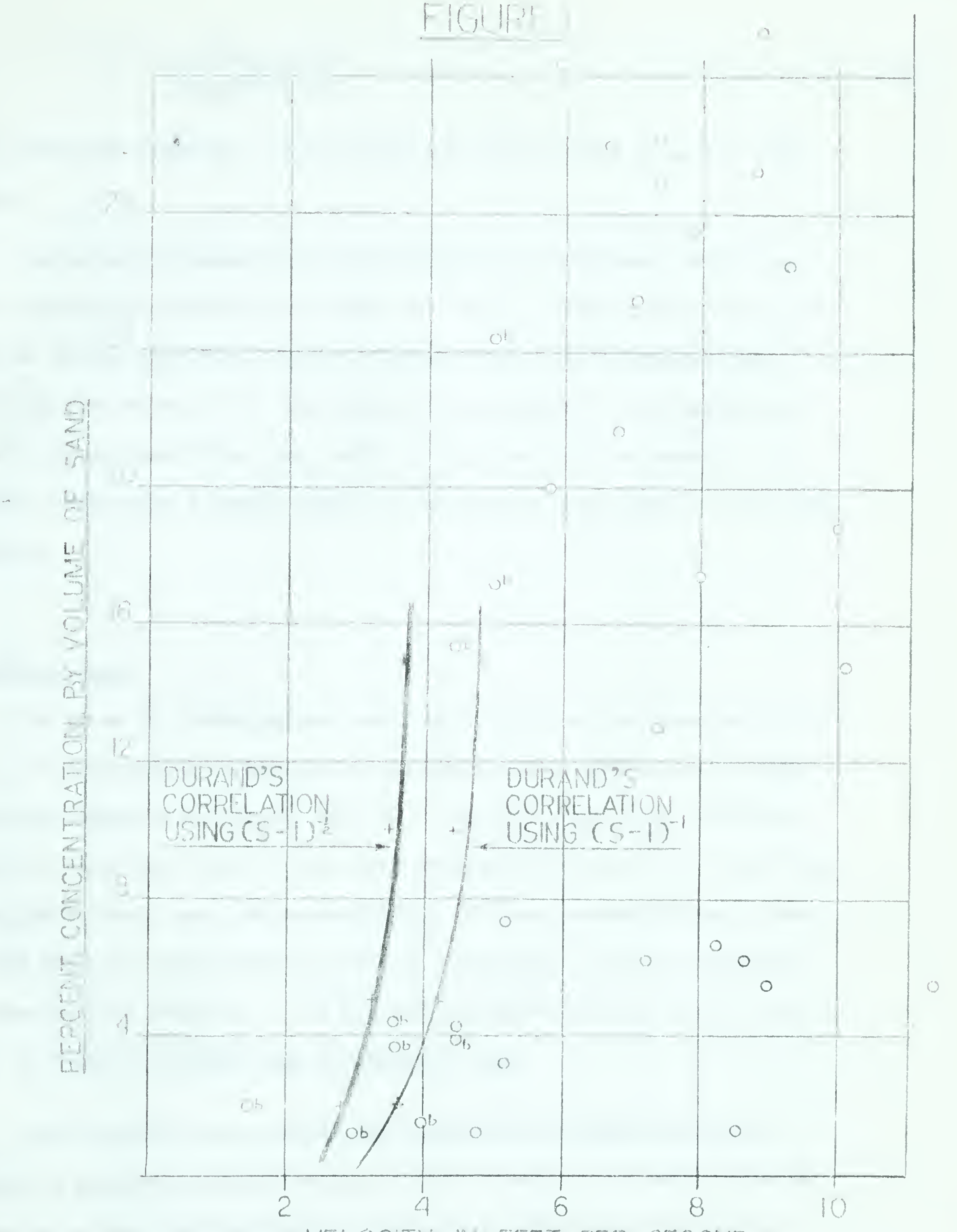
THE EFFECT OF SETTLING VELOCITY ON DURAND'S EQUATION.

FIGURE 11



DURAND'S CORRELATION FOR CRITICAL VELOCITY.

FIGURE 1



"b" INDICATES BED IN PIPE, o U of A, + DURAND'S CORRELATION

COMPARISON OF DURAND'S CRITICAL VELOCITY TO U of A DATA FOR SAND WATER MIXTURES IN 2" PIPE.

$$F_L = \frac{V_c}{(2gD)^{\frac{1}{2}}(s-1)} \quad \text{.......................................} \quad (13a)$$

for the 2-inch pipeline. This has been plotted on FIG. 12 as the light curve.

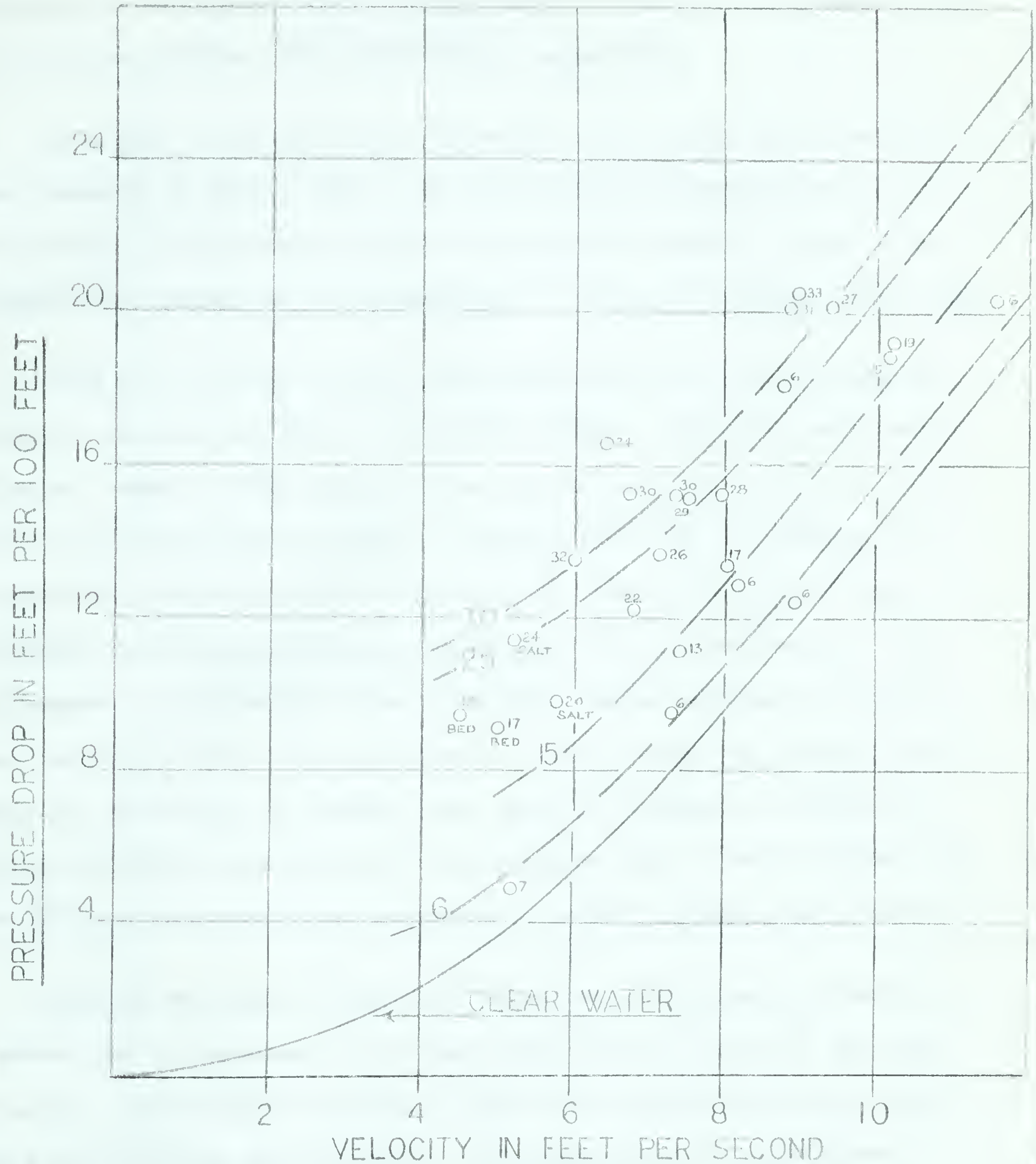
The velocity-pressure drop relationships for different concentration sand-water slurries can be seen in FIG. 13. These curves are quite similar to the published curves of Durand (Ref. 6) and Worster (Ref. 5). The only discrepancy is in the degree of convergence of the sand-water slurry curves toward the clear water line as velocity increases. The Alberta tests show a lesser degree of convergence than those of the other workers.

Fines-Water Tests:

Two types of investigations were carried out on the fines-water slurries. A rheological investigation was performed by others and has been reported summarily by Ansley (Ref. 2). Basically, the study indicated that the fines-water slurry exhibited rheological properties of the Bingham plastic model when the concentration of fines exceeded 6% by volume. Durand (Ref. 6) states that his work on fines-water slurries indicated Bingham plastic behaviour. The hydraulic gradient testing at the University of Alberta included some one hundred runs.

The fines-water mixtures at low concentrations exhibited similar hydraulic gradient characteristics to that of water. In fact, up to 6% fines by volume, the test results indicate no difference from similar tests for water. No doubt the instrumentation inadequacies failed to measure the slight effect of the fines at these low concentrations.

FIGURE 13



NOTE:

NOTE- NUMBERS REPRESENT SAND CONCENTRATION BY VOLUME IN PERCENT

PRESSURE DROP VS VELOCITY
FOR SAND WATER MIXTURES IN 2 INCH PIPE

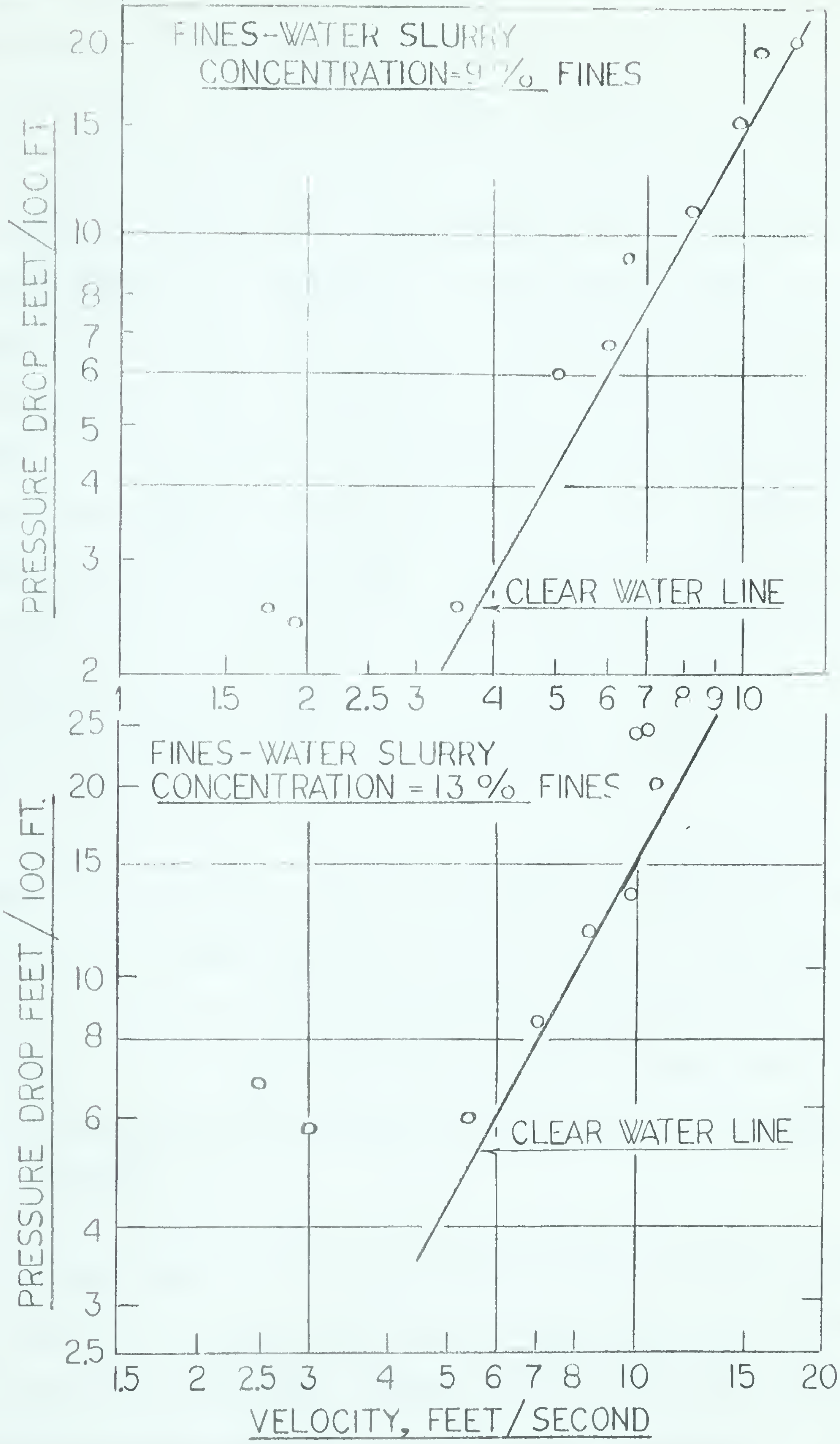
As the concentration of fines increased above 6%, the effect of the fines became quite noticeable. FIG. 14 shows plots of velocity vs. pressure drop for slurries of 9% and 13% concentration, respectively.

The change in characteristics above 6% fines is quite consistent with the discussion of Ansley (Ref. 2) on the rheological characteristics of the slurry. He has pointed out that the apparent kinematic viscosity increases quite rapidly as the concentration of fines is increased above 6-8%.

Using FIG. 6 of Ref. 2 and a fines concentration of 9%, the apparent kinematic viscosity at 25°C. is 2.7×10^{-5} ft.^{2}/sec. Using this value and a Reynolds' number of 2000, laminar flow would be expected in a 2" pipe at a velocity of 0.315 feet per second. Examination of FIG. 14, showing the pressure drop velocity relationship for a 9% fines slurry in a 2" pipe, indicates that laminar flow occurred at about 2.0 feet per second. This corresponds to a Reynolds' number of 12,400. Govier and Charles (Ref. 8) have pointed out that the yield stress of a fluid modelling Bingham plastic behaviour can extend the laminar flow regime up to Reynolds' numbers as high as 100,000. Examination of the rheological data of Ref. 2 showed that the 9% fines slurry could be considered to exhibit Bingham plastic behaviour.

Although the theory (Equation 4) shows that the increase in hydraulic gradient due to the presence of fines varies with the square of the flow velocity, the rheological aspects of the slurry extend the laminar region where this relation does not apply. This combination of two different regimes may be used as an explanation for the fines-water curves which are shown on FIG. 14.

FIGURE 14



PRESSURE DROP VS VELOCITY FOR FINES-WATER MIXTURES IN 2 INCH PIPE.

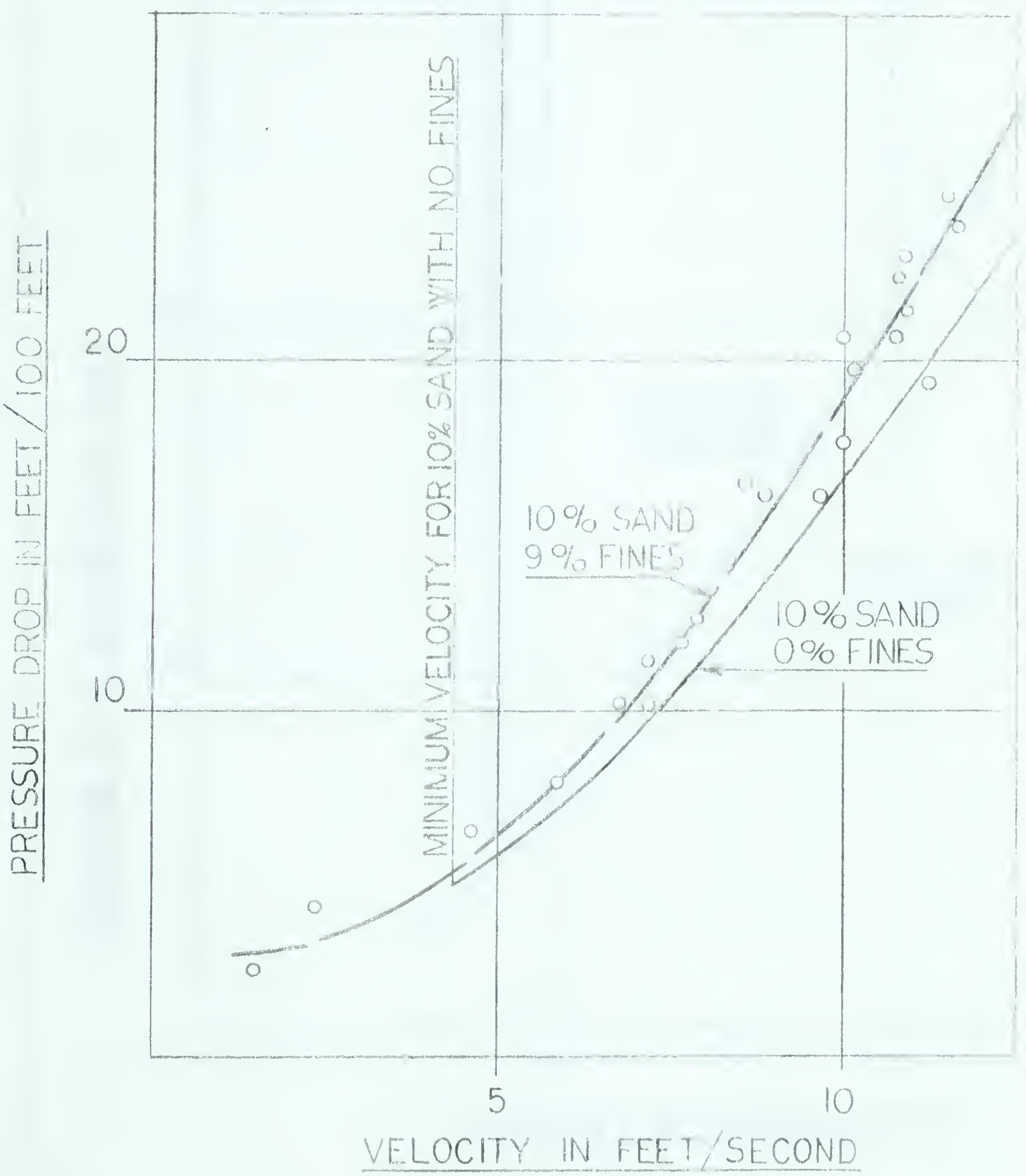
Sand-Fines-Water Tests:

Approximately 150 three-component slurry tests were carried out during the study. As already discussed, the range of fines concentrations tested was limited because of the flume tests being operated concurrently. Newitt (Ref. 7) and Durand (Ref. 6) have discussed the changeover from homogeneous to heterogeneous flows for sand-fines-water slurries. This transition takes place at a velocity which is dependent on both the concentration of fines and of sand. Newitt (Ref. 7) has discussed the attendant problems of testing these slurries and has suggested plotting velocity of flow vs. concentrations of solids at a constant pressure drop. Here again, the author was unable to gather data for such a plot because of the objectives of the overall research program. However, it was possible to select sufficient data to show the effect of the fines on the pressure drop characteristics of the mixture.

FIGURES 15 and 16 show a comparison of various concentration sand-water slurries to the same concentration slurries with fines added. At low velocities the two curves converge, which is consistent with the theory of Eqn. 10. At higher velocities the predicted additional head loss due to the fines can be noted as the displacement of the upper curve from the sand-water curve.

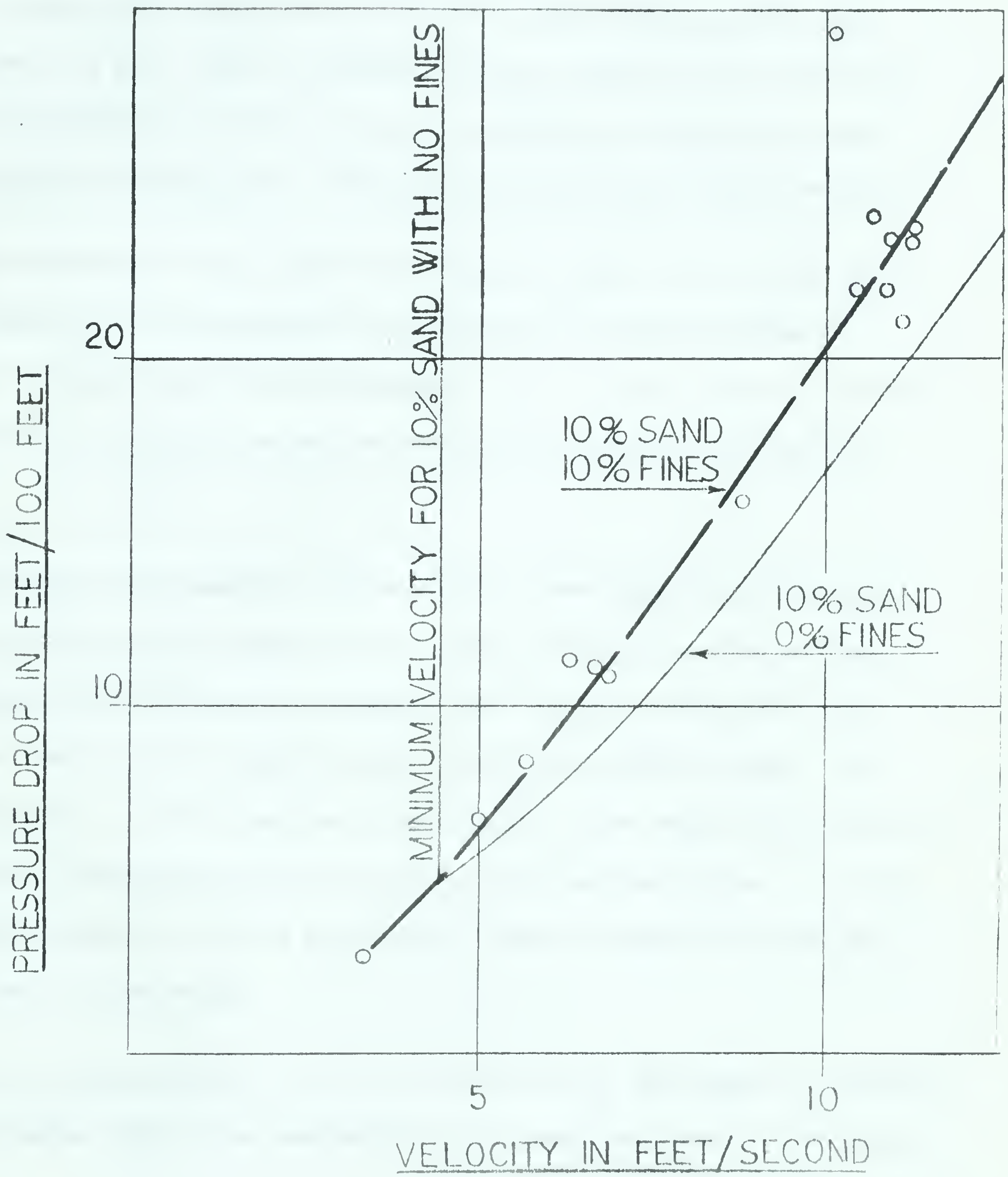
The critical velocity for the sand-water curve is marked on both FIGURES 15 and 16. The presence of the fines has definitely lowered the critical velocity in both cases. However, the data are not extensive enough to determine the degree of critical velocity decrease as a function of concentration of fines. This effect is consistent with that described by Ansley (Ref. 2) for flume transport of the same slurries.

FIGURE 15



EFFECT OF 9% FINES ON A 10% SAND SLURRY

FIGURE 16



EFFECT OF 10% FINES ON A 10% SAND SLURRY.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions:

The apparatus, described herein and in the references, has been developed to a point where reasonable accurate results can be obtained. The instrumentation is simple but quite adequate and has proven versatile enough to overcome many difficulties encountered by other workers.

The sand water slurry tests for pressure drops in the 2-inch pipe agree closely with the published correlations of Durand and Newitt. The data indicate that Durand's parameter for critical velocity requires ammendment for 2-inch pipes and an alternative parameter has been put forth.

Although this research program did not investigate the rheological characteristics of the fines-water slurries, there are sufficient data published by other workers to conclude that the slurries exhibit non-Newtonian behaviour at concentrations greater than 6% by volume. The Bingham plastic yield stress can extend laminar flow regime thus altering the hydraulic characteristics of the slurry at low velocities. In fully developed turbulent flow the presence of fines increases the head loss above that of clear water.

In a fines-sand-water slurry, the fines do not decrease the hydraulic gradient below that of the sand-water slurry over the range of the test results.

Although the data are inconclusive, there is sufficient evidence to suspect that the addition of fines to a sand-water slurry will reduce the critical velocity.

Recommendations:

The analysis carried out in Chapter IV has shown the significant effect of the settling velocity of the sand. There is an unfortunate coincidence that the transition from homogenous flow to heterogenous flow takes place at a particle size where settling velocity is poorly understood. A comprehensive research program should be undertaken to investigate the settling velocities of particles in the size range from 0.15 mm. to 2.0 mm. in water and fines-water slurries. This is the most important variable to be isolated and studied at this time.

As previously discussed the range of fines concentrations tested was not adequately covered. The potential benefit of a reduction in critical velocity in commercial scale applications justifies not only more studies on the present apparatus, but a similar investigation at a larger scale.

LIST OF REFERENCES

Ref. 1 - Ansley, R. W.; Hebbert, R. H. B.

"Moving Hydraulic Jumps in Fluidized Solids Systems," 1961.

Transactions of the Engineering Institute of Canada, Vol. 5, Nº 2, 1961.

Ref. 2 - Ansley, R. W.

"The Effect of Slimes on Open-Channel Transport of Fluidized Solids," June, 1962. Paper Nº 21 presented at the Annual General Meeting of the Engineering Institute of Canada, June, 1962 (to be published in E.I.C. Journal).

Ref. 3 - Ansley, R. W.

Ph.D. Thesis (forthcoming).

Ref. 4 - Cities Service Athabasca, Inc.

"Sand Slurry Test Programme Conducted at University of Alberta," 1960.

Unpublished interim report - April 1960 to September 1960.

Ref. 5 - Worster, R. C.

"Hydraulic Transport of Solids," November, 1952.

Extracts from the Proceedings of a Colloquium on the Hydraulic Transport of Coal held by "The National Coal Board Scientific Department" in London, England.

Ref. 6 - Durand, R.

"The Hydraulic Transportation of Coal and Solid Material in Pipes," November, 1952.

Paper presented at the London Colloquium of The National Coal Board, November 5, 1952.

Ref. 7 - Newitt, D. M., et al

"Hydraulic Conveying of Solids in Horizontal Pipes," 1955. Transactions of The Institute of Chemical Engineers, Vol. 33, Page 93, 1955.

Ref. 8 - Govier, G. W.; Charles, M.

"The Hydraulics of the Pipeline Flow of Solid-Liquid Mixtures," 1961.
The Engineering Journal, Page 50, August 1961.